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PROCEEDINGS

OF THE SECOND NATIONAL CONFERENCE ON AGRICULTURAL TRANSFORMATION

19-20 NOVEMBER 2025
ADDIS ABABA

Proceedings of the Second National Conference on Agricultural Transformation held at the Ethiopian Agricultural Transformation Institute (ATI)

Theme: Accelerating Agricultural Transformation Through Innovative Interventions

November 19-20, 2025
Addis Ababa

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Sustainable Agricultural Intensification and Climate Resilience

Youth and Women Empowerment and Policy Support

Digital Agriculture and Financing

Market Linkages, Value Chain Development, and Agro-Processing

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Preface

It is with great pleasure that we present the Proceedings of the Second National Conference on Agricultural Transformation, a platform convened by the Ethiopian Agricultural Transformation Institute (ATI) to advance Ethiopia's journey toward a competitive, resilient, and inclusive agricultural sector. Building on the momentum of the first conference, this second convening reaffirms ATI's commitment to driving agricultural transformation through science, innovation, and strong partnerships.

Since its establishment, the ATI has played a pivotal role in supporting Ethiopia's agricultural transformation agenda by promoting evidence-based planning, piloting and scaling innovative solutions, and strengthening coordination among public, private, and development actors. In line with this mandate, the Second National Conference on Agricultural Transformation was organized under the theme *"Accelerating Agricultural Transformation through Science, Innovation, and Partnership,"* reflecting the Institute's conviction that sustainable transformation requires knowledge-driven action and collective effort.

The conference was held from 19–20 November 2025, bringing together researchers, policymakers, development practitioners, and partners from across the country and beyond. The forum served as a vibrant space for knowledge exchange, reflection, and dialogue on priority issues shaping Ethiopia's agricultural transformation. A total of 42 peer-reviewed papers were presented, contributed by the ATI, national universities, agricultural research centers, and partner organizations. These papers were organized under six major sub-themes that collectively capture the breadth, complexity, and interconnected nature of the transformation agenda.

The first sub-theme, Agricultural Transformation, examined institutional, policy, and technological pathways for achieving sustained and inclusive growth. The second, Scaling Up and Replicating Successful Interventions, explored mechanisms for expanding proven innovations to achieve system-wide impact. The third sub-theme, Sustainable Agricultural Intensification and Climate Resilience, focused on productivity-enhancing approaches that safeguard natural resources and strengthen resilience to climate shocks. The fourth, Youth and Women Empowerment and Policy Support, highlighted inclusive strategies that promote dignified employment, women's economic empowerment, and gender-responsive policies. The fifth sub-theme, Digital Agriculture and Financing, underscored the growing role of digital technologies and innovative financing models in improving access to information, services, and markets. The sixth sub-theme, Market Linkages, Value Chain Development, and Agro-Processing, emphasized value addition, market connectivity, and agro-industrial development as key drivers of competitiveness and income growth.

Taken together, the papers compiled in this proceeding provide rich insights into both the opportunities and challenges shaping Ethiopia's agricultural transformation. They underscore the central role of science and evidence in informing policy and practice, the power of innovation in addressing systemic bottlenecks, and the importance of collaboration across institutions and sectors. As such, this publication serves as a valuable resource for policymakers, researchers, practitioners, and development partners committed to advancing a resilient, inclusive, and market-oriented agricultural sector.

We extend our sincere appreciation to all authors, reviewers, experts, and participants whose contributions ensured the success of the conference and the quality of this publication. We also acknowledge the continued support of the Government of Ethiopia, development partners, and stakeholders who remain steadfast in their commitment to Ethiopia's agricultural transformation.

It is our hope that this second proceedings volume will further stimulate learning, inform decision-making, and inspire collective action toward a more prosperous and sustainable agricultural future for Ethiopia.

Mandefro Nigussie (PhD)
Chief Executive Officer, ATI

Acknowledgement

The Editorial Team of the Second National Conference on Agricultural Transformation Proceedings extends its sincere appreciation to all individuals and institutions whose commitment and contributions made this publication possible.

First and foremost, we express our deep gratitude to the senior leadership of the Ethiopian Agricultural Transformation Institute (ATI) for their continued vision, guidance, and unwavering support in institutionalizing a culture of knowledge generation and publication. Their endorsement of the conference and the proceedings process has been instrumental in strengthening ATI's role as a knowledge-driven transformation institute.

We wish to express our profound gratitude to Dr. Dagnachew Lule for his visionary leadership, unwavering encouragement, and dedicated guidance in steering the committees and fostering an enabling environment for the preparation and successful execution of this workshop. His tireless commitment and strategic direction have been central not only to the smooth organization of this event but also to establishing a lasting tradition of a scientific forum that promotes knowledge exchange, collaboration, and innovation.

We would like to acknowledge the ATI Publication Committee for its sustained leadership and technical oversight throughout the conference and publication process. The Committee's dedication in refining submission guidelines, overseeing the peer-review process, and upholding academic and professional standards ensured the quality and credibility of this second proceedings volume. We also extend our appreciation to ATI staff members who supported the coordination, planning, and timely execution of the conference and publication activities.

Our sincere thanks go to all authors and co-authors from ATI, national universities, agricultural research centers, and partner institutions who responded to the call for papers and shared their work and experiences. Their willingness to engage in multiple rounds of review and revision, and their openness to constructive feedback, significantly strengthened the analytical depth, clarity, and practical relevance of the papers included in this volume. We are equally grateful to the reviewers and subject-matter experts, both within and outside ATI, who generously dedicated their time and expertise to the rigorous review process.

Finally, we extend our heartfelt appreciation to all conference participants, partners, and collaborators whose engagement enriched the dialogue and knowledge exchange during the Second National Conference on Agricultural Transformation. It is our hope that this proceedings volume will serve as a valuable reference for policymakers, researchers, practitioners, and development partners, and contribute meaningfully to ongoing efforts to advance Ethiopia's agricultural transformation.

Opening Remark

Your Excellency Dr. Mandefro Nigussie, Director General of ATI,
Your Excellencies,
Distinguished Guests,
Esteemed Researchers and Academicians,
Representatives of Development Partners,
Ladies and Gentlemen,

It is a great honor to welcome everyone to the Second National Conference on Agricultural Transformation, organized by the Ethiopian Agricultural Transformation Institute (ATI). I sincerely thank all participants universities, research institutions, regional bureaus, development partners, private-sector actors, and innovators whose presence shows our shared commitment to creating a more resilient, prosperous, and competitive agricultural future for Ethiopia.

Agriculture in Ethiopia is more than just a single sector; it is the foundation of our economy and the livelihoods of millions. It secures our food supply, fosters rural prosperity, and supports our inclusive development path. However, we gather at a time when global agriculture faces numerous challenges, such as climate change, limited resources, population growth, market instability, and geopolitical conflicts. These issues make transforming agriculture essential not only for Ethiopia's future but also for global stability, sustainability, and collective progress.

Ladies and Gentlemen,

Transformation today cannot be achieved through incremental change; it requires leapfrogging. This calls for bold vision, innovative breakthroughs, scientific excellence, resilient institutions, and the collective strength of strategic partnerships. These principles underpin Ethiopia's emerging sectoral innovation system—an integrated ecosystem in which knowledge, technology, governance, markets, and human capability work together to drive structural transformation in agriculture.

This year's conference theme, "Accelerating Agricultural Transformation through Innovative Interventions," reflects this ambition. It challenges us to connect research with practice, anchor policies in evidence, and translate innovation into tangible and measurable impact—especially for farmers, youth, women, and rural communities. It also calls us to look beyond today's constraints toward tomorrow's opportunities: precision agriculture, digital intelligence, climate-resilient systems, and competitive value chains.

The Ethiopian Agricultural Transformation Institute remains the key driver of this mission. Through analytics, systems thinking, digital platforms, and multi-

stakeholder collaboration, ATI offers vital leadership in evidence-based planning, market development, productivity improvement, and resilience building. This conference stands as a testament to ATI's growing role as a center of knowledge and innovation for transformation.

Over the next two days, 42 scientific, learning, and policy papers will be presented by experts from ATI, universities, research centers, development organizations, and the private sector. These contributions reflect a dynamic and growing ecosystem of knowledge one that increasingly links laboratories to fields, policy insights to action, and innovations to measurable outcomes.

The conference is structured around six strategic sub-themes, each aligned with Ethiopia's long-term vision for agricultural transformation:

- Agricultural Transformation for Sustainable Advancement
- Scaling Up and Replicating Successful Interventions
- Sustainable Agricultural Intensification and Climate Resilience
- Youth and Women Economic Empowerment and Policy Support
- Digital Agriculture and Rural Financing
- Market Linkages, Value Chain Development, and Agro-Processing

Together, these themes present a clear roadmap toward an agricultural system that is adaptive, knowledge-driven, digital, climate-smart, inclusive, and globally competitive. They remind us that transformation is not only about increasing production, it is about empowering people, strengthening institutions, and building modern systems that connect farmers to technologies, markets, finance, and opportunities.

The Government of Ethiopia remains firmly committed to this agenda. Under the visionary leadership of the current administration, we are:

- Strengthening institutions and governance systems,
- Modernizing extension and advisory services,
- Expanding digital and data-driven agriculture,
- Promoting agribusiness and agro-industrialization,
- Scaling climate-smart and regenerative practices, and
- Creating dignified employment for youth and women through programmes such as ADEY.

Our flagship initiatives the Agricultural Commercialization Cluster (ACC), Integrated Agro-Industrial Parks, digital innovation platforms, market system reforms, and the forthcoming Farmer-Producer and Agribusiness Companies (FPAC) are central to driving Ethiopia's structural transformation and competitiveness.

The insights and recommendations emerging from this conference will directly help shape these national priorities. They will strengthen our strategies, enhance coordination, and deepen collaboration with development partners—whose support, expertise, and solidarity we greatly value. Together, we are advancing Ethiopia's agricultural and food-systems transformation in alignment with the SDGs and Africa's Agenda 2063.

Ladies and Gentlemen,

As we begin our deliberations, I encourage all of us to adopt the mindset of transformation guided by evidence, driven by innovation, and united in purpose. Let this conference be more than a platform for sharing knowledge; let it be a space where partnerships are forged, ideas become solutions, and solutions translate into measurable impact on the ground.

Together, let us reaffirm our commitment to building an agricultural system that is productive, sustainable, inclusive, and globally competitive a system that upholds dignity, strengthens resilience, and delivers prosperity to every Ethiopian farmer and household.

With these remarks, it is my distinguished honor to declare open the Second National Conference on Agricultural Transformation.

Thank you.
H.E. Dr. Efa Muleta
State Minister of Agriculture, Ministry of Agriculture (MoA)

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Horticulture Farmer Production Cluster: Achievement and Prospects

Weyessa Garedew*, Tesfaye Tadesse, Techane Adugna, Kassa Yihun, Zerihun Abebe, Desalegn Duguma, Mulugeta Fetene, Kindie Aysheshm, Tadesse Teweldebrhan, Fassil Beyene, Yeshiwas Alemnew, Tadesse Tilahun, Kifle Bekele, Getinge Mideksa, Solomon Hailu and Dagnachew Lule

Agricultural Commercialization Cluster (ACC) Vertical, Ethiopian Agricultural Transformation Institute, P.O. Box 708, Addis Ababa, Ethiopia
*Corresponding Author: weyessa.garedew@ati.gov.et

Abstract

The horticultural sector is crucial for economic growth and for improving the dietary diversity in Ethiopia. The crops are very diverse and have different constraints along the value chain. The Horticulture Farmers Production Cluster project (HFPC) was designed as one project under the Agricultural Commercialization Cluster program to improve the livelihood of farmers by increasing production of the five priority horticultural commodities (avocado, mango, banana, tomato, and onion). The project has been implemented in 17 woredas of five regional states (Oromia, Amhara, Tigray, Sidama and south Ethiopia) from 2020/2021 to 2023/2024. The objective of this report is to summarize the major achievements, challenges and the lesson learned of the project. Data were collected on the number of farmers accessing input and extension services, number of clusters established, productivity and productivity gain of priority crops, surplus sold, and number of infrastructures established, and others. The achievement indicated that over 102,200 smallholder farmers were registered and organized under 1617 HFPCs. The total land area covered by HFPC priority commodities was 24,211 ha*. The productivity gains of the five-priority commodities were fundamental when compared to the Ethiopian Statistic Service (2022) data; tomato (846%), onion (263%), banana (244%), mango (511%) and avocado (418 %). About 21 fruit nurseries, 10 roadside market sheds and collection centers and 64 zero cooling chambers were established to enhance marketing of the produces. The results were encouraging and strengthened the evidence that clustering approach is an effective driver of commercialization. It is highly recommended to scale up the intervention.*

Keywords: Clustering, Commercialization, Marketing, Nurseries, Productivity

1. Introduction

Ethiopia is a country with great variety of climate and soil types that can grow diverse horticultural crops for home consumption and foreign markets (Selamawit and Tesfaye, 2019). The horticultural sector is crucial for economic growth and for improving the diet diversity in Ethiopia (SNV, 2019). Currently, most of the horticultural crop products come from the smallholder farms. The crops are very diverse and have different constraints along the value chain. Limited availability of seeds/seedlings and inputs like fertilizers and pesticides, lack of adequate post-harvest management, insufficient extension services due to limited trained manpower and limited knowledge and skills needed in the complex horticultural production process are among the major issues faced by horticulture farmers. Moreover, public research on horticultural technologies is insignificant and major public policies and attention of extension agents were mainly focused on staple crop production (MoFED, 2010).

Based on growing demand for fruits and vegetables, especially in the major cities, the horticultural sector is gaining importance in the country and intensification is slowly starting to take place (Wiersinga and de Jager, 2009). To improve the nutritional status of the population and accelerate other positive development impacts, pathways and strategies for sustainable intensification need to be identified for horticultural crops value chains in Ethiopia (Akalu and Jochen, 2016). The Agricultural Commercialization Cluster (ACC) has set an ambitious target to improve the livelihood of farmers by increasing the production of five priority horticultural commodities: avocado, mango, banana, tomato, and onion, to help meet demand and substitute imports by increasing yield and land under cultivation. Agricultural clustering plays a vital role in promoting regional economic growth, strengthening rural competitiveness, advancing the specialization of agricultural production, and increasing farmers' incomes. As an approach, cluster farming is central to agricultural commercialization, as it enhances the quality of horticultural products through the adoption of high-quality inputs and improved farming practices. It also enables farmers within a cluster to collectively access markets, serve larger buyers, strengthen their bargaining power, and benefit from economies of scale.

In this context, the Horticulture Farmers Production Cluster (HFPC) Project was designed by the Ethiopian Agricultural Transformation Institute (ATI) and implemented across five regions: Oromia, Amhara, Tigray, Sidama, and South Ethiopia, as a comprehensive value chain, based intervention. The project primarily focused on farmer-level interventions by organizing producers into clusters to improve economies of scale and enhance agronomic practices.

The objective of the HFPC project was to act as a delivery mechanism to contribute to the Agricultural Commercialization Cluster (ACC) targets set for the five priority commodities. Therefore, the objective of this paper is to summarize the major achievements and prospects of the HFPC project over project implementation periods.

2. Materials and Methods

2.1. Description of Project implementation sites

Horticulture Farmers Production Cluster (HFPC) was implemented from 2020/2021 to 2023/2024 in 17 woredas of five regions: Oromia (Kersa, Boset, Lume and Ziway Dugda woredas), Amhara (Dera, Fogera, Bahir Dar Zuria and North Mecha woredas), Sidama (Dale, Shebedino, Wondogenet), South Ethiopia (Mirab Abaya and Arba Minch Zuria woredas) and Tigray (Mereb Leha, Lailay Mayichewu, Alamata and Raya Azebo). During the first year (2020/2021), the project was piloted in 11 ACC horticulture woredas while 17 ACC horticulture woredas were considered starting from year two implementation. The target beneficiaries include male and female smallholder farmers that were organized in clusters.

2.2. Cluster formation criteria

Cluster formation criteria were developed based on farmers' production status, particularly the land allocated to horticultural crops and the number of fruit trees owned (Table 1). In addition, farm contiguity within a radius of 1–3 km and farmers' willingness to participate in cluster farming were considered essential criteria for cluster establishment. The existing agronomic management and extension access is weak, which also affects the design of

cluster formation criteria. The horticultural agronomic practices are complex and need precision compared to grain crops production.

Table 1: Cluster formation criteria for HFPCs

Commodity	Minimum requirement per smallholder farmer	Requirement per HFPC (Minimum land/number of trees)
Onion/Tomato	0.25 hectares	5 hectares
Avocado	20 trees	500 trees
Banana	300 trees	5,000 trees
Mango	15 trees	500 trees

Source: Horticulture Farmers Production Cluster Project Design

2.3. Major intervention areas

The interventions were grouped into three support areas. The first intervention was formalization and cluster formation that enable clusters to be officially recognized by supporting bodies. The second intervention was capacity building by providing training to cluster member farmers to create adequate awareness on HFPC. the third intervention involved the provision of input and infrastructure development such as nurseries to increase the production and productivity of the horticulture priority crops. This support also included the marketing of horticultural produces through facilitating market linkages and establishing roadside market sheds and collection and aggregation centers.

2.4. Data Collection and Analysis Methods

The achievements were summarized by compiling the four years data that were collected from project implementation districts and summarized in the form of quarterly and monthly Project Management Office (PMO) report, quarterly parliament and annual donor reports. These data include the number of farmers' production clusters established, the number of smallholder farmers involved in cluster formation, the area that was covered by HFPC, the productivity of each horticulture priority crop, the volume of production, number of nurseries established, number of roadside market sheds , collection and aggregation centers established, and others. The collected data were summarized using descriptive analysis and presented as a result. The summarized data was presented using Tables and Figures.

3. Results and Discussion

3.1. Horticulture Farmer Aggregation

The four-year project achievement indicates that about one hundred thousand (102,200) (Figure 2) smallholder farmers have been registered and organized under 1617 HFPCs (Figure 1). The total land area covered by HFPC by priority commodities was 24,211 ha. The number of farmers registered varies among the horticulture priority crops. More farmers were organized together as clusters to produce avocado compared to the other crops (Figure 1). The achievement also indicated that the number of farmers involved in cluster farming was increasing for all the priority crops indicating that the adoption of cluster farming among smallholder farmers. Horticulture Farmers Production Cluster plays key roles

in smallholder farmers commercialization by ensuring product quality by adopting high quality inputs and enhanced farming practices and enable clusters to access markets together to serve larger buyers, strengthen negotiation power, and benefit from economies of scale.

However, the number of clusters established (1617, representing 11.12% of the target 14,538) and the number of smallholder farmers registered under clusters (~102,200, representing 29 % of the target 357,175) were below the target of the project design. The target indicated on the project design was not achieved because of several factors. The perennial nature of the crops, security problems, competition with irrigated wheat initiative for vegetable crops, ambitious target during the planning and the delay in the implementation of the project by one year are some of the factors associated with the low achievement of the target indicated on the project design. Moreover, the transformation of HFPC into a fully functioning farmers production company has not been realized as planned in the project design because most of the clusters existed at basic and intermediate stages. In some regions, the farmers in the cluster were organized as cooperatives to facilitate their horticultural crops production and marketing. For example, commercial avocado producing Farmer Production Cluster (FPC) were organized at Lume Woreda (Oromia region) as *HUNDAOL Fruit and Vegetable Producing and Marketing Cooperative* for facilitating Avocado export. Similarly, in the Amhara region, farmers in clusters were organized as *Selam Fruit and Vegetable Producing and Marketing Cooperative* to facilitate their avocado export.

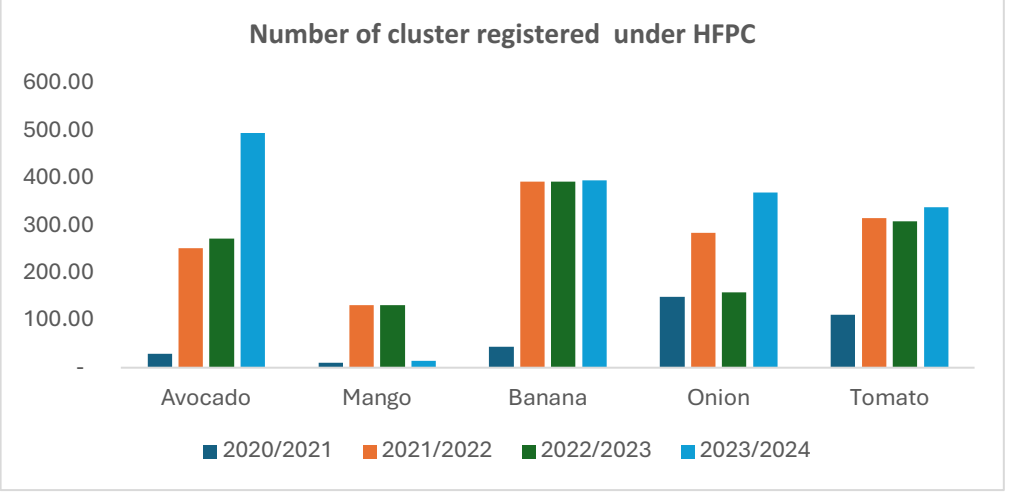

Figure 1. Number of clusters established under Horticulture Farmers Production Cluster

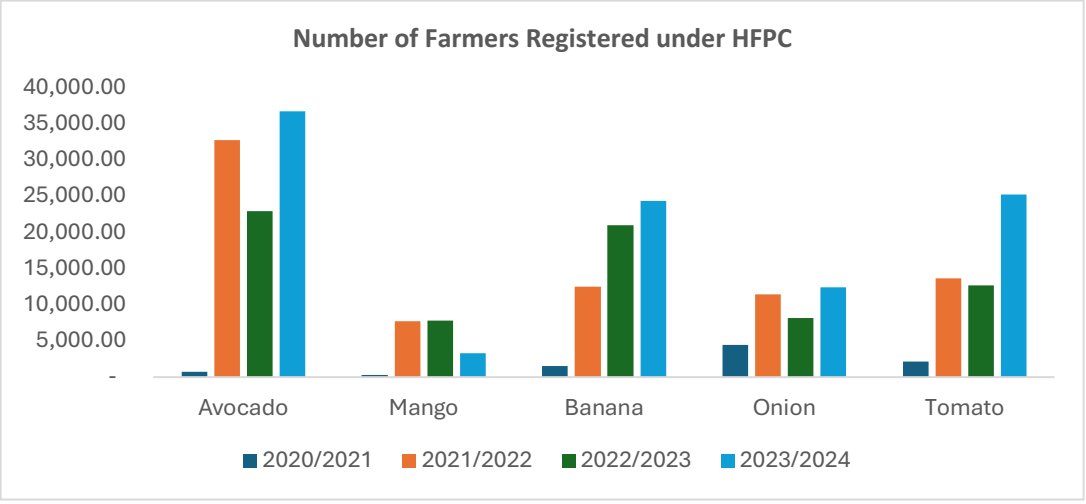

Figure 2. Number of Farmers Registered under Horticulture Farmers Production Cluster

3.2. Farmers' access to input and financial services

Expanding access to inputs is one of the most critical components in horticulture farmers production clusters as it is less developed compared to that of the grain production. As such, to enhance the availability of seedlings for fruit production, the HFPC project built/upgraded 21 fruit nurseries in five regions, which are currently serving as sources of fruit seedlings across the different parts of the country. Accordingly, over the project duration about 77,800 smallholder farmers have obtained access to improved seedlings/seeds. This is an encouraging result as about 76% of the farmers registered under clusters obtained improved seedling/seed of horticultural crops from the established nurseries. In addition to the 21 completed nurseries, the establishment/upgrading of about five nurseries were started in the Tigray region although they are not completed due to the conflict in the area. Overall, during the project implementation period, about 931,250 seedlings of different fruits (avocado, mango and banana) were distributed to smallholder farmers by the project.

Furthermore, to enhance the availability of quality rootstock and scion materials for avocado propagation, seven clonal gardens (Wayu Tuka and Kersa in Oromia region and Shoa Robit and Woramit in Amhara region and Dagia, Aruma and Chano Mille in former SNNP region) were established/upgraded during the project implementation period. These clonal gardens are equipped with different facilities such as net sheds, irrigation system (reservoirs, pipeline, solar powered pump), pump house, polyhouse, fence, guard house, toilet…etc. These clonal gardens have been used as source of rootstock and scion materials for avocado propagation for the different regions.

Access to credit is another important enabling factor for farmers' access to input, production and productivity. This can help farmers to improve their productivity, increase their income, and reduce their risk. However, according to PMO data, access to credit was very limited as the proportion of farmers benefited from this service was only about 35% over the project implementation periods.

3.3. Adoption of improved production practices

To increase the adoption of improved horticultural crops production technologies several activities were implemented over the project implementation periods. To update the horticulture production technology, horticultural crops production package revision was done in collaboration with the Ministry of Agriculture and respective regional bureaus of agriculture. Moreover, several horticultural crop technologies were also demonstrated to enhance the adoption of improved technologies. The production/multiplication of onion seeds using bulb-to-seed method was undertaken by organizing FPC farmers in demonstration with the aim of ensuring access to quality and traceable seeds at affordable prices within the FPCs. For example, in the Amhara region, FPC farmers received 360 qt of onion bulbs from the project team and produced more than 30 qt of onion seeds (Figure 3).

Figure3. Demonstration of onion seed production from bulbs at Fogera in 2013 EFY

The clustering approach is a key strategy of the FPC to increase production and productivity by enabling farmers to gain access to full packages technologies, including use of improved agronomic practices. Accordingly, over 187 full package demonstrations were conducted on different priority horticultural crops (106 for tomato, 45 for onion, and 36 for avocado) across different locations of ACC woredas (Figure 5). These demonstrations increased the adoption of full packages technology by FPCs farmers. In addition to demonstration activities, several technical and practical capacity-building training sessions on different topics were held for FPC farmers, development agents, agricultural experts and other stakeholders. The major training topics covered include the concept of HFPC, full package technologies, business development, irrigation agronomy, climate smart agriculture, crop protection, post-harvest handling, governance and leadership skills for FPC leaders, nursery management and grafting (Figure 4), contract farming and others.

Figure 4. Demonstration of full package on tomato (A) and capacity building training on avocado grafting (B)

To further enhance the adoption of horticultural technologies by FPCs farmers, several field days were conducted across regions. Farmers' field days and experience sharing were conducted at different times and locations.

Production of vegetables under protected environment is one of the production methods used to increase the volume of production and productivity. This type of production system needs the construction of modern greenhouse. However, the construction of greenhouse needs high capital investment, and the smallholder farmers are not able to construct such greenhouses. Therefore, the HFPC project constructed six modified greenhouses (polyhouses) from locally available materials and demonstrated intensive tomato production (Figure 5). The constructed polyhouses are equipped with solar powered pump for water distribution system (irrigation).

Figure 5. Demo on tomato production in the polyhouse in Dera Woreda, 2014 EFY

3.4. Horticulture Crops Production and Productivity

According to the PMO data, except mango the productivity of priority horticultural crops under FPC showed an increasing trend over the implementation periods (Figure 6). There was also variability in productivity among the crops over the implementation periods. This variability might be associated with different factors such as the type of varieties used in each production year (e.g. tomato) and environmental factors such as drought (e.g. banana). The reduction of mango productivity over the years could be associated with the infestation of white mango scale insects that poses considerable challenges to mango production.

The productivity values recorded under FPC for the priority horticultural commodities were very high compared to the Ethiopia Statistical Service (ESS) data during the respective year. The four-year average yield of avocado, banana, mango, tomato and onion under FPC was 365 qt/ha, 535 qt/ha, 361 qt/ha, 649 qt/ha and 255 qt/ha respectively (Table 2). The productivity gains of the five-priority horticultural commodities were fundamental when compared to the ESS (2023) data; tomato (846%), onion (263%), banana (244%), mango (511%) and avocado (418 %) (Table 2), which shows the effectiveness of the farmers production cluster approach. The variation of the yield data between ESS and FPC data might also be linked with the sample size and management intensity applied. The ESS calculates the yield of horticultural commodities based on sample data collected predominantly from area of rain-fed production, whereas the FPC is implemented in areas with intensive production system including irrigation. As such, the FPC performance is considerably higher than what is reported by ESS. Moreover, the FPC data was collected from the FPC established in 17 woredas of the country, which are very small compared to the total horticulture producing woredas of the country, where ESS is based for data generation.

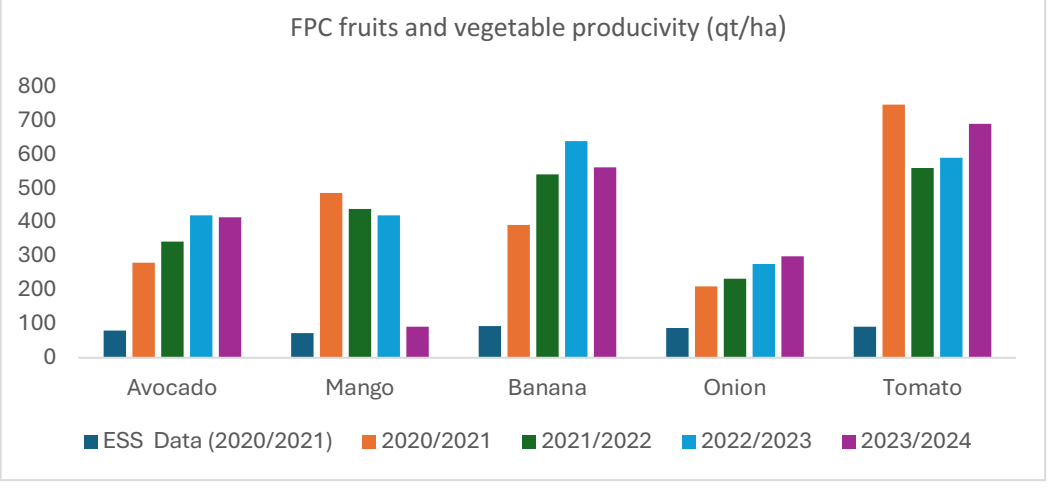

Figure 6. Productivity of priority horticultural commodities

Table 2. The average yield and the productivity gains FPC with ESS

	Avocado	Banana	Mango	Tomato	Onion
ESS 2021/2022(qt/ha)	70.5	155.4	59.1	68.6	70.3
Average four-year FPC (qt/ha)	365	535	361	649	255
% increase FPC Vs ESS	418	244	511	846	263

Similar to the progress shown in the productivity of the horticultural crops, the PMO data indicates higher production rate in HFPC. About 28 million quintals of horticultural produces were produced under the FPC over the project duration (Figure 7), achieving the targeted total volume of production 100% indicated in the project design. Moreover, the volume of production for the five horticulture commodities showed an increasing trend over the implementation periods except banana production in 2022/2023 cropping season. The increase in volume of production for the five-priority horticultural commodity is also linked with the expansion in area under FPC over the implementation periods except mango. The high reduction in volume of production (~57% less production) in banana in 2022/2023 cropping season might be associated with the low rainfall (drought) occurred in Arba Minch, the main banana producing cluster in Ethiopia.

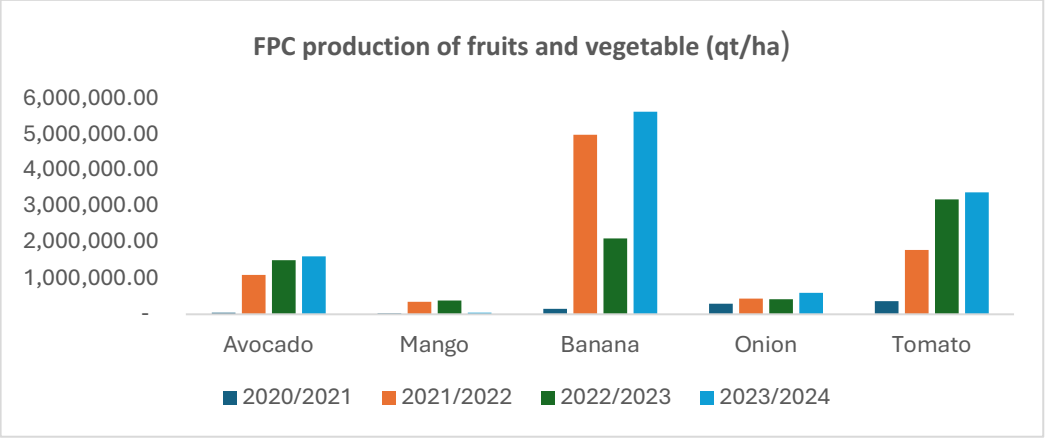

Figure 7. Production volume of the five priority horticulture commodities under FPC from 2020/2021 to 2023/2024.

3.5. Improved adoption of pre- and post-harvest technologies

Post-harvest loss is one of major problems among the horticulture value chain. To address this problem, the implementation of low-cost storage facilities plays a vital role in extending the shelf life and reducing the physiological weight loss of the high value horticultural crops. Accordingly, the HFPC project constructed 64 Zero Energy Cooling Chamber (ZECC) (2 by Oromia Agricultural Transformation Centre (OATC) in Oromia, 7 by Amhara Agricultural Transformation Centre (AATC) in Amhara, 55 by South Agricultural Transformation Centre (SATC)) in model farmers' farm for demonstration (Figure 8). ZECC can retain the quality and extend the shelf life of high value horticultural commodities by reducing the temperature and keeping the humidity high for the produces.

To reduce post-harvest loss, the project also purchased four cold trucks (3 in Oromia region and 1 in the former SNNP) and handed over to end users during the project implementation periods. These tracks are very important for the transportation of high value horticultural crops from production areas to marketing areas. The project has also provided capacity building training for several participants on post-harvest handling.

Figure 8. Demonstration of Zero energy cooling chamber

3.6. Access to Market

With production and productivity targets attained, it is vital to establish and strengthen market linkages for farmers to sell their produce, resulting in a direct impact on their incomes. Improved farmer yield and higher prices led to an increased marketable surplus since farmers are encouraged to sell what has left of their household consumption. Horticulture value chains are considerably less developed than grain crop commodities, particularly when it comes to market channels. To improve the marketing channel, the HFPC project conducted several Value Chain Alliance (VCA) meetings among the stakeholders involved in horticulture value chain. In this forum many stakeholders were involved including smallholder farmers, buyers, traders, experts, processing industry and others. This meeting forum provided a platform for stakeholders to discuss the marketing challenges encountered and outline future direction for improvement, and lesson learned. The forum was arranged in each quarter for each priority crop. This linkage and coordination among stakeholders improved access to the market for FPC farmers and solved their major challenges related to marketing and other production related problems.

To improve access to market for FPC farmers, the HFPC project constructed 10 roadside market shades and collection and aggregation centers (5 in Oromia, 3 in Amhara and 2 in former SNNP). These facilities enhanced farmers' access to the market as they enabled them to sell their produces at the center very easily (Figure 9).

Figure 9. Mojo (left) and Batu (right) roadside market sheds in East Shewa zone, Oromia

Furthermore, the HFPC project conducted awareness creation training on contract farming proclamation and technical guidelines for experts, traders, aggregators, development agents and other stakeholders to enhance the marketing of horticultural commodities. The identification of top buyers' demands, negotiation and contract agreement signing, regular supervision, backstopping, and technical support were done over the project periods. Accordingly, the average percentage surplus sold for the five horticultural commodities over the last four years was 83 %. However, it should be noted that contract farming is more challenging for horticultural crops due to high broker involvement. Hence, farmers are discouraged from supplying through contract farming, and buyers are uninterested in contractual agreements due to no enforcement mechanism exercised yet.

Over the project period, avocado and banana export was facilitated by the project in two regions: Oromia and Amhara. Accordingly, 5761 quintals of avocado (Oromia and Amhara) and 600 quintals of banana (Oromia) were exported to international and regional market respectively. The project also created enabling environment by supporting Selam and Hundaol horticulture and vegetable production and marketing cooperatives in getting Global Good Agricultural Practices (Global GAP) certificate, which is prerequisite for the export of produces into the international market. This support was given to the indicated cooperative every year since the certificate need renewal each year. Moreover, to support Selam and Hundaol fruit and vegetable production and marketing cooperatives, awareness creation training and discussion was conducted on Avocado Good Agricultural Practices certification process with the presence of certification advisory service providers, respected experts and FPC farmers in collaboration with the Agricultural Investment and marketing team.

4. Conclusion and Recommendations

The Horticulture Farmers Production Cluster is a promising approach for commercializing horticulture farmers. The project significantly increased productivity and income for farmers by improving access to horticultural inputs, a major bottleneck for smallholder farmers, through the establishment of nurseries and greenhouses. It also established infrastructure like roadside market shades and aggregation centers to facilitate marketing. The HFPC project's results were encouraging, demonstrating that cluster farming is an effective driver of commercialization and value chain development, significantly boosting production and productivity of priority crops. This approach has been fully adopted by the Ministry of Agriculture. Established platforms like VCAs have been instrumental in addressing shared challenges and promoting accountability among stakeholders.

However, the number of clusters in ACC-I was limited, necessitating further expansion and strategic interventions. Insufficient involvement from financial institutions has hindered capital accumulation necessary for advancing FPCs. Challenges include the inability to hand over procured agricultural machinery and established infrastructure to FPCs, as they lack legal status. The policy team of the ATI is working on a legalization framework for FPCs as a priority. Furthermore, limited access to inputs (seeds, fertilizers, agro-chemicals) and financial services hinders the adoption of full package technologies, resulting in poor productivity. Security issues and competition from irrigated wheat farming for land have also affected FPC expansion in horticulture ACC districts. Additionally, outbreaks of diseases and pests, such as the white mango scale insect, have discouraged farmers from investing in crops like mango.

Therefore, further expansion and strategic interventions are crucial, including engaging public and private sectors for input supply and extension services to enhance the dissemination of improved production technologies for a sustainable value chain. The existing clusters are basic and not yet at the company level, highlighting the need to advance them into farmers' producer companies in ACCII. Additionally, investment in cold chain technologies, such as cold storage and transportation, is essential for high-value crops. It's also important to empower FPC members to view their initiatives as business ventures.

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Transformational Status of High-Value Crop and Livestock Farms in the Central Oromia Region, Ethiopia

***Chala Hailu[1],Gabriele Canali[2], and Vincenzo Tabaglio[3]**

[1] Faculty of Agriculture, Department of Agro-Food System, Universita Cattolica Del Sacro Cuore, Piacenza, Italy, and Lecture at the Department of Agricultural Economics, Ambo University, Ethiopia. Email: P.O.Box 19.
[2] Univerisita Cattolica Del Scaro Cuore, Department of Agri-Food Economics, Piacenza, Italy.
[3]Universita Cattolica Del Scaro Cuore, Department of Sustainable Crop Production, Piacenza, Italy.
*Corresponding author email: caalaa2012@gmail.com

Abstract

Transforming farm systems by integrating high-value crops and livestock is vital to achieving food security in Ethiopia. This study assessed the transformation status of such integration at the farm household level and identified key influencing factors. Conducted in five districts of West Shewa and Southwest Shewa zones in central Oromia region, the study used a multi-stage sampling technique to collect primary data from 422 farm households. Data were analyzed using descriptive statistics and an ordered probit model. The results indicated that 49.22% of households had partial transformation, 28.65% medium, and 22.13% full transformation status. Landholding size and livestock ownership were positively associated with medium and full transformation levels. Adoption of crossbred cows, improved egg-laying poultry, and herbicide use increased the likelihood of reaching medium or full transformation, while having a negative association with partial transformation. Practices such as seed saving, labor hiring, and market contract participation also supported transformation, though lack of credit access hindered progress beyond partial transformation. Additionally, greater distance from veterinary services decreased the likelihood of full transformation. The findings highlight the role of socio-economic diversity in influencing transformation patterns and underscore the need to revise technology dissemination and institutional support strategies under Ethiopia's agricultural transformation policy.

Keywords: Farm Households, High-Value Farm Products, Ordered Probit Model

1. Introduction

Transforming farm systems by integrating high-value crops and livestock is vital to achieving food security in Ethiopia. Hence, the 2030 agenda for sustainable development have opened opportunities to transform the food and agricultural systems to bring down hunger to zero. It is evidenced that global agricultural production and food systems halted by the dynamics changes in world population, and complex environmental calamities(DeBenedetti, 2021). Likewise, migration from rural-to-urban is at glance move and the sedentary aging farmers limits supply of agricultural labor force which reduces the role in food production (FAO, 2017). These facts have tremendous effect on sustainable agriculture in developing regions where urbanization is growing, and food production is dominated by smallholder farmers.

The post-World War II agricultural growth shows the fast pace of industrial agriculture where production was boosted using agricultural technologies. Nevertheless, such booming in agricultural production overlooked the stewardship of the resource basis and ended up by top soil degradation, and loss of biodiversity (Gliessman, 2014). Consequently, episodes

in agricultural growth showed unsustainable. Therefore, the 1990 sustainable agriculture bill in USA define as "an integrated system of plant and animal production practices having a site-specific application" that over long run will achieve social, economic and environmental goals (Velten *et al.,* 2015). This dignifies the 1987th Brundtland definitions for sustainable development which concerns for justice for alleviation of poverty (UN, 1987). Specifically rural poverty reduction requires stability of food systems, through balancing production with consumption.

For instance, Ethiopia adopted transformational agricultural policy to address the goal of sustainable agriculture. Agriculture is rain-fed based and climate change threats food production. The transformation agenda allows farmers to use intensively purchased inputs to increase production. This lies in the definitions of agricultural transformation refers "as process that leads to higher productivity on farms, commercially oriented farming, and strengthen the link between farming and other sectors of economy" (AfDB, 2016). It focuses to address volume, value and change agent's interconnectedness and structural changes: in industry land scape, relative decline share of GDP in agriculture, demographic transitions, high value chain developments (Pritchett, 2013). Explicitly, transformation is the path way for sustainable agricultural development which requires innovations that complement production techniques fits to environmental management (Adnan *et al.*, 2018). It is believed to raise labor productivity and paves mobility to non-agricultural activities, and obtain higher prices for agricultural outputs (Bosc *et al.*, 2012; de Vries *et al.*, 2015; Lewis, 1954; Timmer & Akkus, 2008).

Hence, most findings suggested there is success story of sustainable agricultural production through integrated crop-livestock farming systems which have great role to improve material and social need in both rural and urban areas (NwachukwuI,2008). Notably, it enhances food security by supporting biodiversity conservation(Danso-Abbeam *et al.*, 2021; Gliessman, 2014). Therefore, this study was initiated to investigate farmers' transformative changes focusing on mixing high-value crops and livestock production decisions.

For the next 30 years, the African labor force is estimated to grow to 800 million and total population reached to 2.5 billion in 2050, and with majority will living remain in rural which needs attention to sustainable rural economy (Tom *et al.,* 2019). This calls to balance sustainable food production with population growth. Now days, sustainable agriculture and food systems have gotten attention from academician and policy makers all over the world. The challenge arising from global climate change and exponential growing of populations in developing countries cautioned to future healthy food provision. Accordingly, different approaches were made to address challenges to agricultural sustainability.

Ethiopian government take initiation of intensification of high-value cereal crops such as teff, wheat, malt barely, and maize (ATA, 2013). However, advocacy to intensification requires access to cheap purchased inputs and endorsement of specialization (European Commission, 2017). Despite numerous studies on agricultural transformation, limited attention has been given to how mixed high-value crops and livestock enterprises are evolving at the household level. Understanding the current transformation status and its determinants is essential for shaping effective policies that promote sustainable and inclusive agricultural development.

Therefore, the general objective of this study is to assess the status of transformation in mixed high-value crop-livestock enterprises and identify factors influencing transformation among farm households in the study areas. The specific objectives of this study are to describe the key characteristics of mixed high-value crop-livestock enterprises in central Oromia and to identify and estimate factors affecting the transformation status of these enterprises.

2. Materials and Methods

2.1. Description of the study area

The study was conducted in West Shewa and Southwest Shewa Zones of Oromia Regional State, Ethiopia. These zones are in the central part of Ethiopia, near the capital, Addis Ababa. West Shewa is bordered by the Southwest Shewa Zone and the former Southern Nations, Nationalities, and Peoples' (SNNP)Region to the south, Jimma Zone to the southwest, East Welega Zone to the west, Horo Gudru Welega Zone to the northwest, and the Amhara Region to the north. The capital of the zone, Ambo, lies approximately 114 km from Addis Ababa. The geographical coordinates of the zone are between 8°17'N to 9°60'N latitude and 37°17'E to 38°45'E longitude. West Shewa comprises 20 districts.

Southwest Shewa Zone is bordered by West Shewa to the west, East Shewa to the east, the former SNNP Region to the southeast, and Jimma Zone to the southwest. It is located at approximately 8°36'33.0"N latitude and 38°14'07.2"E longitude. The zone consists of 14 districts, with its capital, Waliso, also situated about 114 km from Addis Ababa. In both zones, the predominant farming system is a mixed crop-livestock enterprise. Major staple cereals include teff, wheat, and barley, while pulses such as faba bean, field pea, and chickpea are widely grown. The zones also have potential for vegetable production. Livestock species commonly kept include cattle, sheep, goats, horses, mules, donkeys, poultry, and bees.

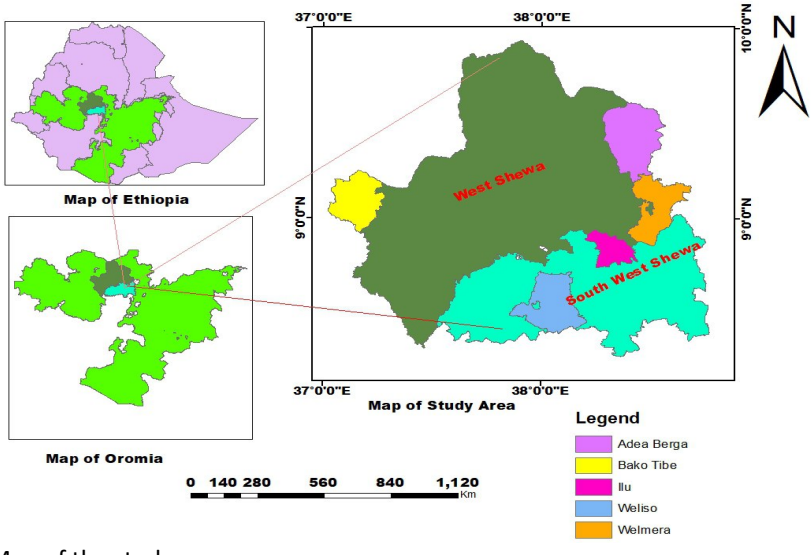

Figure 1. Map of the study areas
Source: GIS laboratory, Ambo University (2024).

2.1. Data Types, and Sources

Both qualitative and quantitative data were collected. Qualitative data captured farmers' behavioral responses to transformation and included open-ended responses. Quantitative data included socio-economic, demographic, institutional, and enterprise-related information, as well as data on physical assets. The primary data sources were farm household heads. To validate the findings, focus group discussions were conducted with groups of farmers to explore the performance of high-value farm enterprises.

2.2. Method of Data Collection

Data was collected using a semi-structured questionnaire comprising both open- and closed-ended questions. The questionnaire covered household characteristics, economic and institutional variables, physical resources, and information on high-value crop-livestock enterprises. Enumerators were recruited and trained prior to the survey. A pre-test was conducted over two days to refine the questionnaire and assess time efficiency. After revisions, the actual data collection was conducted via personal interviews.

2.3. Sampling Method and Sample Size Determination

A multi-stage sampling procedure was employed:

1. **Stratification by Agro-Ecology:** Districts were first stratified into highland, midland, and lowland zones to ensure the inclusion of diverse high-value commodities. For example, maize dominates in low- and mid-altitude zones, whereas teff, wheat, and malt barley are common in mid- and high-altitude areas.

- In West Shewa Zone: 7 districts are highland, 8 midland, and 5 lowlands.
- In Southwest Shewa Zone: 6 districts are highland, 5 midland, and 3 lowlands.

2. District Selection:

- From West Shewa: Ada'a Berga (highland), Welmera (midland), and Bako Tibe (lowland) were selected.
- From Southwest Shewa: Ilu (highland) and Weliso (midland) were chosen.

3. Kebele Selection: Using a 10% sampling intensity based on the rule of thumb by Curry (1984), 15 kebeles were selected from a total of 147:

- Ada'a Berga: 4 kebeles
- Welmera: 3 kebeles
- Bako Tibe: 3 kebeles
- Weliso: 3 kebeles
- Ilu: 3 kebeles

4. Household Selection: A total of 384 farm households were selected using probability proportional to size. The sample size was determined using Cochran's (1977) formula. Hence, under assumption of normal distribution, the precision level calibrated at $\pm$ 5% and the confidence level is 95% showing z-score of 1.96. Then the formula is given as:

$$n_0 = \frac{z^2 pq}{e^2}$$

where, n_0= sample size, z=critical value of desired confidence level, *p*=estimated proportion of an attribute exist in the population, *q*=1-p, and *e*= desired level of precision. Therefore;

$$n_0 = \frac{(1.96)^2 (0.5)(0.5)}{(0.05)^2} = 384.16 \approx 384$$

To account for potential non-respondents, an additional 10% was added to the sample size, resulting in a total of 422 sample farm households.

2.4. Method of Data Analysis

2.4.1. Descriptive and inferential statistics

Descriptive statistics were used to summarize the status of transformation among mixed high-value crop-livestock enterprises. Frequencies and percentages were computed for variables like gender, district-level transformation patterns, and enterprise categories. Data were presented using tables, graphs, and pie charts.

2.4.2. Econometric model specifications

Determining factors affecting farm transformational status at household level.

To identify factors affecting the transformation status of farm households, both ordered logit and ordered probit models were employed. These models are appropriate for analyzing ordinal response variables — in this case, levels of transformation:

- Partial transformation (y = 1)
- Medium transformation (y = 2)
- Full transformation (y = 3)

Marginal effects were computed to interpret how changes in explanatory variables affect the probability of each transformation status.

Categorization of Transformation:

- **Partial Transformation:** High-value crops combined with conventional livestock (e.g., teff + local cattle).
- **Medium Transformation:** High-value crops combined with at least one improved livestock practice (e.g., crossbred dairy, poultry, or fattening).
- **Full Transformation:** Integration of high-value crops with three or more improved livestock enterprises.

This modeling framework captures the heterogeneity of transformation outcomes and helps identify the critical drivers of change across farm households.

Both ordered logit and probit models are used to estimate factors affecting transformational changes by integrating high value crop-livestock enterprises. The logit model follows logistic functions while the probit model is cumulative density functions (CDF). The logit model assumes error term follows logistic distribution, and very simple in computation and revelation of odd ratio values (Greene, 2012) while in probit model the error term is normal distributed. And the standard normal distribution having mean zero and unity variance assumptions prevailed. Moreover, the order probit model fits heterogeneous data generated (Greene, 2012) as the result of respondent background, and agro-ecological

variation of the study areas. For the analysis of ordered, categorical, nonquantitative decisions, outcomes, and responses (McKelvey & Zavoina, 1975) proposed the ordered probit model in its modern form. If the order outcome we consider in transformation change is partial (y=1), moderate (y=2), and full (y=3). The ordered outcome arises sequential as a latent variable, y*, crosses progressively higher thresholds. In this study, y* is an unobserved measure of status of transformational changes for farm households i, specified as follows.

$$y_i^* = x'_i \beta + u_i \tag{1}$$

The latent variable (y*) farm transformational change will exhibit ordinal categorical which is coded as 0,1, 2...j. The response category j is observed when the underlying continuous outcome falls in the j[th] alternative as:

$$\begin{aligned} Y^* &= 0 \; if \; Y^* \le \delta_0 \\ Y^* &= 1 if \; \delta_0 < Y^* \le \delta_1 \\ Y^* &= 2 if \; \delta_1 < Y^* \le \delta_2 \end{aligned} \tag{2}$$

Where a normalization is that the regressors x do not include an intercept. For every high-value crop combined with conventional livestock production system (y*), status of transformation change is partial; for $y^* > \mu_1$, status of transformational change is moderate; for $y^* > \mu_2$, and further improvement in transformation in combining high-value crop-livestock; the transformation status is full. For *k* alternatives ordered status in farm transformation the ordered probit model define as:

$y_i = j$ if $\mu_j - 1 < y_i^* \le \mu_j$, for j= 1,…K (3)

where $\mu_0 = -\infty$ and $\mu_k = \infty$, Then

$$\Pr(y_i = j) = \Pr(\mu_j - 1 < y_i^* \le \mu_j) \tag{4}$$

$$= \Pr(\mu_j - 1 < x_i'\beta + u_i \le \mu_j) \tag{5}$$

$$= \Pr(\mu_j - 1 < x_i'\beta < u_i \le \mu_j - x_i'\beta) \tag{6}$$

$$= F(\mu_j - x_i'\beta) - F(\mu_{j-1} - x_i'\beta) \tag{7}$$

Where F is the cumulative density function (c.d.f) of U_i. The regression parameters βi, and the k-1 threshold parameters $\mu_1, \ldots \mu_{k-1}$, are obtained by maximizing the likelihood with $p_{ij} = \Pr(y_i = j)$ as explained above. The marginal effect provides the direction of the probability for each categorical outcome. It is a positive or negative sign that the variable x_i have on y and illustrated as follows (Green, 2008).

$$\frac{P(y=j)}{\partial x_i} = \left[F'(\mu_k - x_i'\beta\right] - F'(\mu_{k-1} - x_i'\beta)\beta_i \tag{8}$$

Accordingly, there are seven enterprise combinations that are grouped into three categories of transformational status. Enterprise combination is subject to farmers' preferences and motives to produce a given product. On the survey questioner format each enterprise will be listed and marked to indicate it is produced by the respective farmer. After that, for the

sake of investigating the transformational status, the model will be fitted as an ordinary outcome. The first category considers those farmers who are still practicing farming of high value crops (teff, maize, wheat, malt barely, chickpea, vegetables) along with the conventional system in livestock production. In this study the status level of transformational change is considered as partial transformation. The second category includes those farmers who participated in high-value-crop with alternative livestock production (cross breed dairy cow, improved egg layer poultry or sheep or/bull fattening). This category will be labeled as medium transformational changes. The third and the upper groups are those farmers who fully engaged in both high-value crop and livestock production system. The engagement is designated as farmers participated in at least three livestock production strategies.

3. Results and Discussion

3.1. Result of Descriptive Statistics

3.1.1. Descriptions of respondents by farm transformation status

The result of descriptive and inferential statistics is illustrated as outlined below. The result was synthesized from 384 sample farm households that interviewed from five districts in central Ethiopia. The result described in Table 1 below showed that about 321 males and 63 females headed farm households were interviewed. About 206 (48.81%) sampled farm households were in the category of partial status, while 110 (28.91%) and 85 (22.28%) were in the category of medium and full transformation status, respectively. The findings revealed that sex distributions of the sample respondents were larger for male households and had variations across the transformation status in the studied districts.

Table 1.Distribution of Sex of Farm Households by Transformation Status.

Sex of Farm Households	Farm Transformation Status						Overall Total
	Partial		Medium		Full		
	Freq.	Percent	Freq.	Percent	Freq.	Percent	
Male	171	83.01	100	81.97	80	85.11	351
Female	35	16.99	22	18.03	14	14.89	71
Overall	206	48.81	122	28.91	94	22.28	422

Source: Own Survey Data (2024).

3.1.2. Distributions of Farm Transformational Status by Districts

As indicated in Fig. 2 below, the proportions of farm households within and between districts varied by category of transformation status. The output of the '*ggplot'* showed that 39.42% and 7.4% of smallholder farmers from *Ada'a Barga* and *Bako Tibe* districts were in the category of full transformation status, respectively. Conversely, 75.8% and 22.12% of farmers from *Bako Tibe* and *Ada'a Barga* districts fell into the category of partial transformation status. On the other hand, 45.5% of smallholder farmers from *Ilu* district were in the category of medium status. The process of transformational practice in the Welmera and Bako Tibe districts is slow in integrating high-value farm enterprises. While

farmers in Ada'a Barga and Ilu districts showed more advanced transformation practices compared to others.

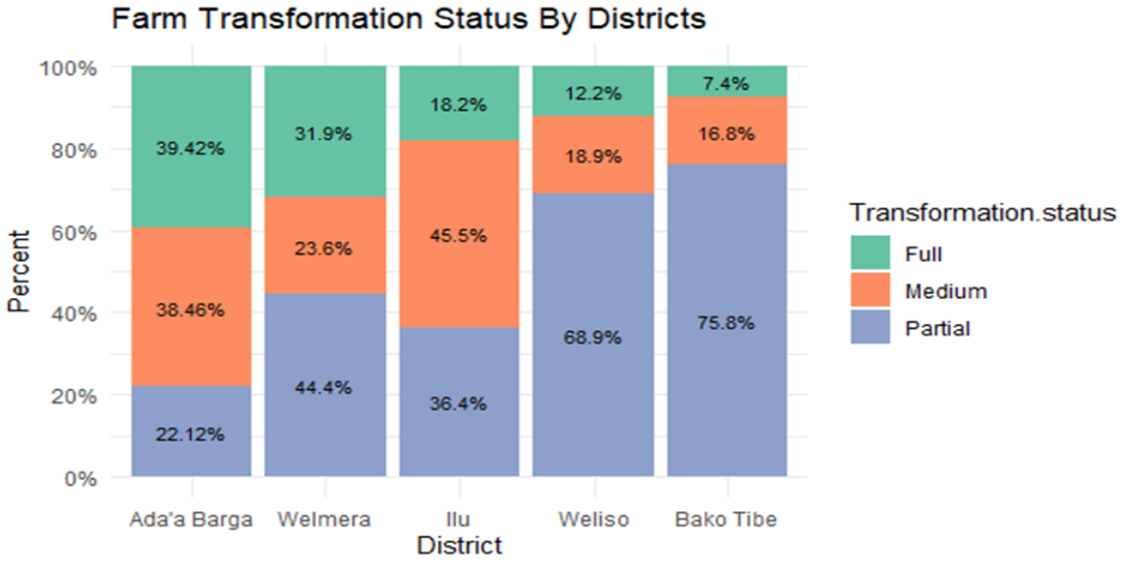

Figure 2. Distributions of Farmers Transformational Status by Districts.
Source: Own Survey data (2024) and computed using R software package.

3.1.3. Distributions of high value farm enterprises by number of farm households

During data collection, farmers were asked to pick the highest value enterprises they perceived for their livelihood sustenance. The typically selected high value crops and livestock enterprises were produced under permissible agro-ecology. Accordingly, majority of farmers produce maize and followed by teff crop enterprise. The adoption of cross breed dairy cow put in third place showing the reflection of farmers' growing interest in diversifying their farm portfolios. However, few respondents reported adopting cross breed dairy cow. And this bounds to farmers' exposure to animal technology constraint and intensity of knowledge acquaint (see Fig. 3 below).

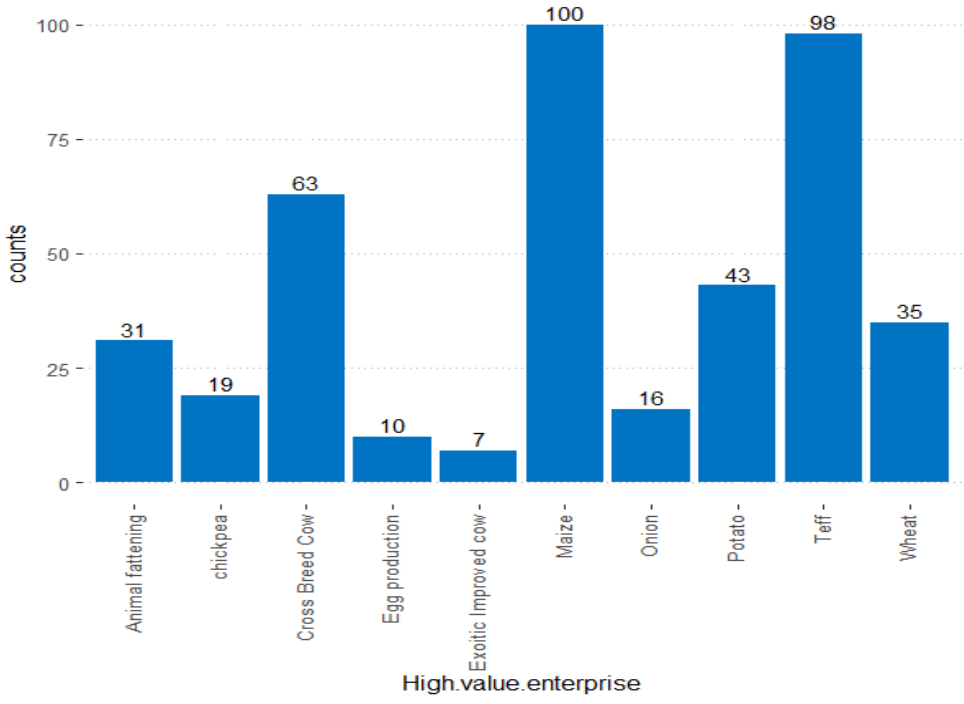

Figure 3. Bar chart of High value enterprises by number of farm households.
Source: Own survey Data (2024) and Computed using R-Software.

3.1.4. Distribution of high value farm enterprises by category of transformation status across districts

The stacked group bar graph below showed the distribution of high-value farm enterprises by category of transformation status in each district. The base of the stacked bars typically represents wheat enterprises across the category of transformation except for *Bako Tibe, Ilu, and Weliso* districts in the category of full transformation. On the other hand, the upper column of the stacked bar graph is filled by animal fattening enterprises. More animal fatteners were from *Ilu* district under the category of medium status, while more crossbreed cows were practiced in *Ada'aa Barga* district. Improved poultry egg layers, chickpeas, and exotic improved cows are more practiced in Ilu district. And maize enterprise is the dominant crop for *Bako Tibe* district across the three categories of transformation status. This may indicate that access to livestock technologies and inputs is better in Ilu and Ada'a Barga than in Bako Tibe. On the other hand, the graph showed that potato is more preferred in *Welmera* district, while onion is a potential crop in *Weliso* district. The improvement in transformational practices through the integration of high-value farm enterprises is observed in all study districts except Bako-Tibe. Generally, the medium and full transformation status is characterized by a diversification of crop and livestock enterprises. In contrast, the partial status is primarily dominated by crop enterprises and shows less integration with other enterprises (see Fig. 4 below).

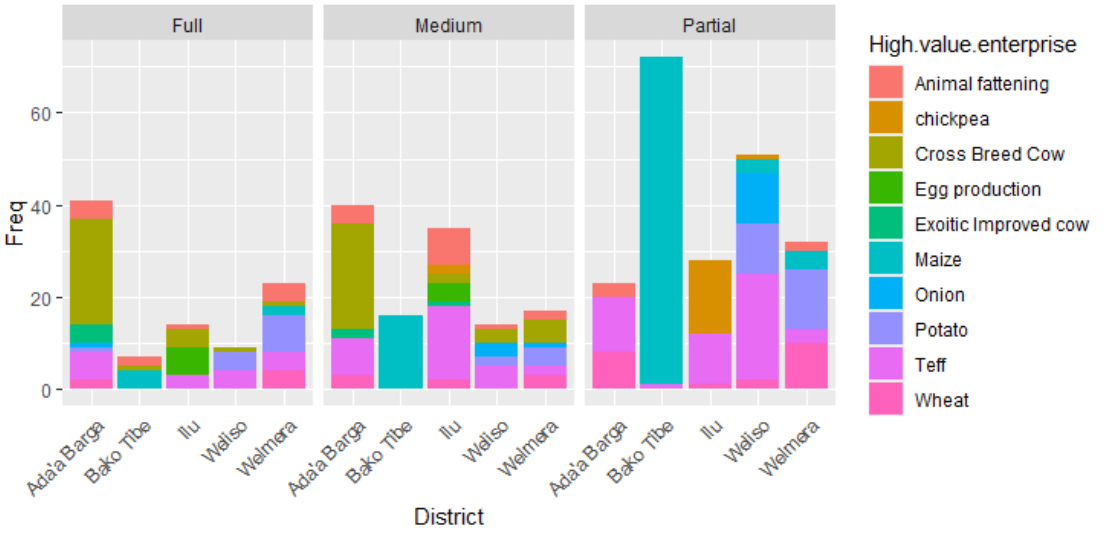

Figure 4. Stack bar graph of high value enterprises by category of transformation status. Source: Own Survey Data (2024).

3.1.5. Farm plowing strategies

The following pie chart (see Fig.5) demonstrates how farmers classify their plowing methods based on the stage of transformation. About 48.61%, 38.36%, and 30.24% of farmers in the categories of full, medium, and partial transformation status, respectively tilled their land through social cooperation and known locally as "*daboo*." Farmers can coordinate labor and ox power with the aid of an informal institution called the "*daboo*." For large-scale farmers, it's the best way to prepare land quickly and efficiently. Hence, developing connections is one of the transformation's key elements. Tractor use is also categorized under this strategy, although only 1.77% of farmers reported using them. The exchange of resources among farm households is improved by the tie of productive farm resources. For instance, farmers who do not have oxen might either rent or engage in cooperative social activities. Therefore, about 7.24%, 6.85%, and 3.04% of farmers in the categories of partial, medium, and full transformation status are rented oxen, respectively. Similarly, the percentage of farmers in the corresponding categories of partial, medium, and full transformation status who plough land with their own oxen is 60.79%, 52.05%, and 46.58%. This reflects an increase in farmers' awareness, government support to improve access to tractors, the facilitation of rental services, and the impact of extension services that advocate for farmers' transformational motives. Another possible reason is that the average land holdings of farmers influence the importance of renting tractors and oxen, as well as participating in "*daboo*," or social cooperation. *This reflects how social capital plays a critical role in mechanization and land preparation, particularly among more transformed farmers.* Overall, the findings demonstrated that the degree of social collaboration and external input purchases, such as renting tractors, increases with the transformative capacity of farmers, highlighting their progress. (see Fig. 5 below).

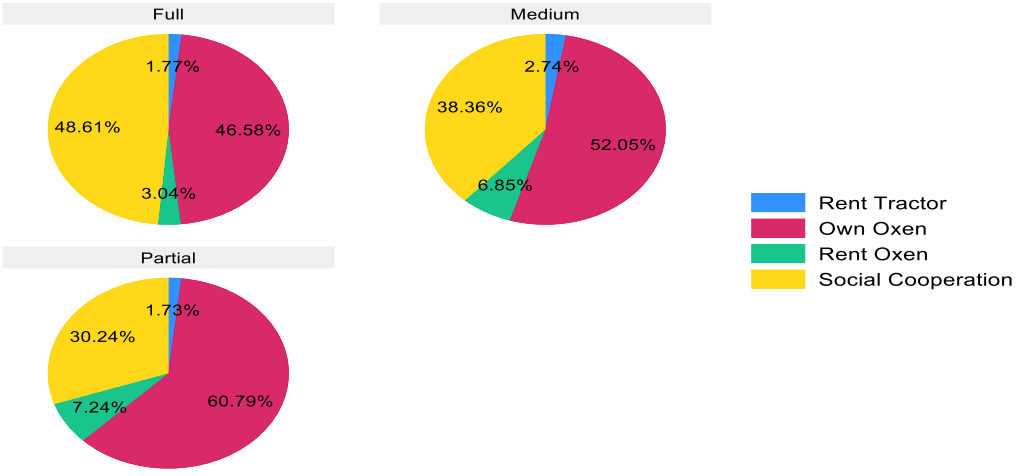

Figure 5. Pie chart of land ploughing techniques by category of farm transformation status.
Source: Own survey Data (2024) and computed using STATA 17.

3.2. Results of Econometric Model

Before the variables were fitted into the model, assumptions were considered to test. The proportional odds assumption, sometimes referred to as the parallel regression assumption, is the main premise of the ordinal probit model (Greene, 2012). This indicates that every predictor variable has the same impact on the result at every level of the ordinal dependent variable (partial, medium, and full). Furthermore, the model makes the critical assumption that the error components are regularly distributed, which is essential for estimating maximum likelihood.

The Multicollinearity test was also performed using the VIF test command in STATA and found an average VIF of 1.23. And showed that there was no serious correlation between the independent variables. In addition, to verify the relationship between independent variables, Pearson's correlation coefficient and Spearman's correlation were used. Following these standard hypotheses, 13 explanatory variables were selected based on a sample size ratio of 1:20. The goodness of fit of the model is indicated by p = 0.000, Wald chi2 = 251.89, and pseudo R^2 = 0.34. Of the 17 explanatory variables, eight of them were statistically significant. Finally, the probability of each ordered dependent variable for the model was also predicted. Then, using the "fx" command, the expected score for each classified variable was evaluated at the mean.

3.2.1. Factors affecting high-value enterprise transformation

The likelihood that farmers will fall into the category of alternative transformation status is influenced by household wealth characteristics, including land size and livestock in TLU. Hence, an increase in land size, improves the probability of the status of integrating high-value farm enterprises to medium and full status by in 4% and 1%, respectively. The variables were statistically significant at P<0.01. It is obvious that land size and livestock assets are promised to diversify farm portfolios. However, land size had decreased the transformation status to the lower category of partial status by 0.067 percentage points (see

Table 2). Land is basic resource to conduct farm business. During the focus group discussion, farmers raised concerns that land limitations and declining soil fertility hinder farm productivity. This issue, coupled with a reduction in grazing land and a lack of forage, constrains the improvement of livestock productivity. This result is consistent with (Malapit *et al.,* 2020), who suggested that socioeconomic considerations had a greater influence on agricultural enterprise diversification than land size alone. This may go against the claim made by (Ricciardi *et al.,* 2021) that small landowners in developing countries have more agricultural landscapes than large landowners, but it is not supported by the result of this study.

On the other hand, farm households continue to engage in livestock farming, which significantly contributes to food security and serves as a source of income. The number of livestock in TLU was statistically significant at P<0.001. Hence, a unit increase in TLU improves the probability of transformation status to the medium category by 1.3%. Farmers can focus more on high-value livestock to achieve economies of scale from farm operations. In addition, it improves the status to a full category by probability of 0.9% (see Table 2). During group discussions, farmers confirmed that having a large herd size is advantageous for replacing some of their cows with crossbred dairy cows available for sale. This shift has resulted in an input substitution effect, motivated by the expected high milk yield from the crossbred cows. This finding is supported by (Byerlee *et al*., 2009; Erdaw, 2023; Sharma *et al.,* 2018) that there is a need for more animal products due to altered consumption patterns brought on by economic growth and also presents a chance for livestock development in agriculture sector. Conversely, the less the livestock in number, decreases the probability of transformational status to partial category by 2.2%. Low herd size may be an indication of small land size which is not enough for grazing, and farmers switched to cultivate crop. According to research conducted in the Democratic Republic of Congo, land-poor farmers are frequently kept low in herd sizes and limited by the availability of grazing fields (Mugumaarhahama *et al.*, 2021).

In addition to land and livestock, other critical factors shaping transformation include labor division, input use, and access to technology. The availability of labor divisions favors enterprise diversification, which improves labor productivity. Likewise, less availability of labor division underscored the number and type of new farm technology adoption, which resulted in inefficiencies. The result in Table 2 below showed the likelihood of less availability of labor division lowers the status of high-value farm enterprise transformation to the category of partial by 1.5%. The lack of labor division is driven by rural-urban migration, where youth are less inclined to engage in family agriculture, resulting in most farmers lacking clear role divisions. Conversely, more labor division availability in a family member improves the probability of status to category of full 3.9% and is statistically significant at P<0.1 (see Table 2 below). This highlights the importance of social networking for the reciprocal services that family labor availability provides. Similar findings argued that the adoption of diversified agricultural technology enhances labour efficiency, which magnifies agricultural transformation (Reardon & Timmer, 2014).

On the other hand, (see Table 2 below) depicted that transformation status was negatively impacted by the usage of insufficient fertilizer. Most farmers stated that fertilizer scarcity influenced their farming decisions during the study period. Improved seed and fertilizer are examples of complementary inputs utilized in farm business operations. However, the

economy deteriorated during the Ethiopian civil war in 2020–2022, and the government ran out of foreign currency to purchase the adequate quantity of fertilizer. Therefore, when farm households apply insufficient amounts of fertilizer, the probability that high-value crop productivity is reduced by 2%, 7%, and 4% to the categories of partial, medium, and full status respectively. Fertilizer distributions for the production year 2022/23 (2016 E.C) are evidently impacted by distributional problems caused by illegal trading and opportunities for bribery. This may be a source of inequality in access to inputs during this period. This implied that low fertilizer use has a direct correlation to slow transformation and lowers high-value crop yields in each status category. Similar vice versa findings in Gahanna demonstrated that increasing fertilizer use is strongly justified for sustainable agricultural intensification if yield response, fertilizer usage efficiency, and the economic viability of fertilizer application are high (Adzawla *et al.*, 2024).

Furthermore, one of the best indicators of farm transformation is the use of mechanization by smallholder farmers, such as the application of herbicides and other agricultural chemicals. Thus, low use of herbicides reduces the probability of being partial status by 40% while keeping other things held constant and statistically significant at P<0.001 (see Table 2 below). Herbicide use among farm households may be influenced by crop intensification and the labor scarcity that some farmers are experiencing. Herbicide treatment is an alternative for farmers facing a labor shortage; however, the quality of herbicides often discourages farmers due to their inefficiency in eliminating weeds. Another similar finding (Tamru *et al.,* 2017) demonstrated that Ethiopia's application of herbicides has led to significant improvements in crop productivity. Nigerian farming practices could change as a result of increased awareness of the usage of herbicides (Adewuyi & Offar, 2022).

Further, institutional factors such as the availability of financial credit requirements are a bottleneck for smallholder farmers to transform high-value farm enterprises. Access to credit is critical to adopting improved agricultural technologies but insurmountable for poor smallholder farmers. Thus, farmers access informal credit through individuals and traders to produce a given high-value enterprise, especially the purchase of seed and fertilizer. A dummy change to credit access increases the probability of being to category of partial status by 81% and statistically significant at P<0.05 (see Table 2 below). Social capitalization can facilitate access to informal credit, while access to formal credit is often hindered by collateral requirements and bureaucratic processes. This finding is similar to studies in Indonesia, China, and Bangladesh by *(*Haryanto *et al.,* 2023*;* Jimi *et al.,* 2016*;* and Lu *et al.,* 2023), respectively, which revealed that improved productivity and technological efficiencies are backed by access to adequate credit.

However, credit access had a negative sign in the category of medium and full status as shown in Table 2 below. Farmers probably lack an adequate amount of credit to purchase improved animal technologies, limiting farmers' demand. In accordance, the lack of credit reduces the probability of improvement of farm transformation status to medium and full by 48%, and 33%, respectively and statistically significant at p<0.05. Formal credit access has a specific process for providing financial services to agricultural development. In such cases, farmers' acquisition of improved technologies is often financially limited, leading them to rely on self-financing or peer financial sources to mitigate the financial constraints faced by their farm businesses. This finding conforms with (Chasama *et al.,* 2023) shows that in Sub-Saharan Africa, breed improvements are influenced by unsustainable financing, weak

coordination, and weak technical bases for animal breeding. A similar finding in Brazil also showed that livestock intensification was limited by access to finance and technical support (Köberle *et al.,* 2023). Therefore, the overall findings revealed that social networking, the adoption of improved agricultural technologies, and farmers' endowment resources (such as land and livestock) significantly influence the advancement of agricultural transformation in the study area.

Moreover, the availability of seed affects crop production, and farmers often save seed from their harvests. However, there is heterogeneity among farmers in developing seed-saving behaviours, which are influenced by farming experience. Thus, a decision to save own seed is associated with a 17.4% decrease in the probability of farmer being in the partial status category. However, it increases the probability of being in the medium and full categories by 11.1% and 6.3 % respectively. The variable seed save was statistically significant at $p<0.01$ (see Table 4). Farmers' understanding of agro-ecological suitability, as well as seed scarcity, drives them to be innovative in adjusting their seed demand. This is particularly important because the Ethiopian seed distribution system is entirely controlled by the public, which has a shortcoming in terms of quantity and quality. Therefore, this finding suggests that farmers, through their experience, are adjusting their innovative strategies to mitigate seed demand, which induces agricultural input transformation. This finding is confirmed by a study conducted in Kenya, which indicates that strengthening smallholder farmers' capacities through organizational frameworks improves farmers' innovative skills.(Eli Wortmann, 2019).

Agricultural transformation is evident when inputs are substituted based on relative input prices. The farm family is a key feature of Ethiopian farmers, as agriculture employs both family labour and hired labour. The decision to hire labour is associated with a 16.4% increase in the probability of a farmer being in partial status, while it decreases the probability of being in medium and full status by 8.3% and 80.4%, respectively (see Table 4). This implies that as the level of transformation improves, farmers adopt mechanisation, which tends to reduce labour-intensive activities. This finding, supported by studies in Haiti (Paul & Régis, 2024) and China (Zou *et al.,* 2024), revealed that the demand for hired labor declined following increasing productivity, in which mechanization played a role in labor dynamics.

Access to credit is essential for adopting advanced agricultural technologies; however, it remains a significant barrier for smallholder farmers. A dummy change in access to credit services was associated with a 15.7% decrease in the probability of a farmer being in partial status. Conversely, it increases the probability of a farmer being in the medium and full status categories by 9.8% and 5.9%, respectively. The variable, credit, was statistically significant at the $p<0.05$ level (see Table 4). This implies that access to credit provides the opportunity to acquire improved agricultural technologies, thereby enhancing the progress of farm transformation. This finding is similar to studies in Indonesia, China, and Bangladesh by (Haryanto *et al.*, 2023; Jimi *et al.,* 2016; Lu *et al.,* 2023), which indicate that access to sufficient credit supports enhanced productivity and technological efficiency.

The distance from veterinary clinic services influences farmers' adoption of improved dairy and poultry practices. Specifically, poultry diseases are very common in rural areas, which reduces farmers' adoption rate. Accordingly, an increase in distance from local veterinary

services was associated with a 9.6% increase in the probability of a farmer being in partial status, while it reduced the probability of being in full status by 3.9%. This finding was statistically significant at the $p<0.05$ level (see Table 4). This suggests that farmers who are far from veterinary services are less likely to adopt improved livestock breeds due to frustration from livestock losses, which has negative implications for the progress of livestock transformation. During field surveys, farmers expressed their reluctance to adopt improved egg-laying poultry primarily due to concerns about poultry diseases. This aligns with the findings of (Korir *et al.,* 2023; Minten *et al.,* 2020), which indicate that herd size and location significantly influence the adoption of improved livestock breeds while controlling for other factors.

Table 2. Result of Ordered Probit Regression Model Estimation at Marginal Effect.

Variables	Dependent variables = Status of Farm Transformation								
	(1)=Partial (n=206)			(2)=Medium (n=122)			(3)=Full (n=94)		
	dy/dx	Std. Err	P>|Z|	dy/dx	Std. Err	P>|Z|	dy/dx	Std. Err	P>|Z|
Agehh	-0.002	0.002	0.805	0.001	0.001	0.806	0.003	0.001	0.805
FamilyS	0.007	0.012	0.587	-0.004	0.007	0.586	-0.003	0.005	0.589
Educa	0.001	0.007	0.906	-0.001	0.004	0.906	0.001	0.003	0.906
LandS	-0.067	0.024	0.005***	0.04	0.015	0.008***	0.027	0.01	0.007***
LaborDiv*	-0.105	0.062	0.09*	0.065	0.041	0.108	0.039	0.022	0.074*
Adeqfert*	-0.022	0.068	0.08*	-0.076	0.047	0.106	-0.044	0.023	0.052*
TLU	-0.022	0.005	0.000***	0.013	0.004	0.000***	-0.009	0.003	0.000***
IrigPart*	0.087	0.054	0.106	0.051	0.031	0.100	-0.036	0.024	0.129
UseHrbcid*	-0.404	0.074	0.000***	0.301	0.066	0.000***	0.103	0.018	0.000***
FrqExtCo	-0.006	0.028	0.822	0.004	0.016	0.821	0.002	0.011	0.822
AvCrdt*	0.081	0.037	0.03**	-0.048	0.022	0.033**	-0.033	0.016	0.037**

(*) dy/dx is for discrete change of dummy variable from 0 to 1

Result of ordered probit regression model estimation at marginal effect (Cont'd…)

Explanatory variables	Dependent variable = Transformational status of high-value farms								
	(1) =Partial (n=206)			(2) =Medium (n=122)			(3) =Full (n=94)		
	dy/dx	Std. Err	P>|Z|	dy/dx	Std. Err	P>|Z|	dy/dx	Std. Err	P>|Z|
Save own seed*	-0.174***	0.061	0.004	0.111***	0.042	0.009	0.063***	0.021	0.003
Hire labor for farming*	0.164***	0.061	0.008	-0.083***	0.028	0.003	-0.804**	0.036	0.027
Access to credit services*	-0.157**	0.064	0.014	0.098**	0.043	0.023	0.059***	0.023	0.009
Market-oriented production*	0.016	0.055	0.758	-0.010	0.033	0.759	0.007	0.022	0.757
Shared experience*	-0.050	0.066	0.448	0.029	0.037	0.437	0.021	0.029	0.466
Frequency of extension service	-0.012	0.027	0.647	0.007	0.016	0.645	0.005	0.011	0.650
Distance from nearest market in hour	-0.044	0.041	0.284	0.026	0.025	0.289	0.017	0.016	0.285
Distance from veterinary services	0.096**	0.049	0.049	-0.057	0.030	0.059	-0.039**	0.019	0.046
Log pseudo likelihood =-290.38									
No. of Obs. =422									
Wald chi2 (17) =251.43									
Prob.>chi2=0.000									
Pseudo R2=0.3381									

(*) dy/dx is for discrete change of dummy variable from 0 to 1
p<0.01 (***), & P<0.05(**). Source: Own Survey Data (2024).

4. Conclusion and Recommendations

Farm-level decision-making plays a crucial role in the adoption of high-value crop and livestock enterprises. This study assessed the transformation status of these enterprises—categorized as partial, medium, and full—and identified the major factors influencing their progression. The findings show that most farmers remain in the partial transformation stage, with only a small proportion reaching full transformation. This disparity is closely linked to variations in agroecological conditions and differences in market proximity.

In particular, the adoption of productivity-enhancing technologies such as cross-breed dairy cows, improved egg-laying poultry breeds, and modern weed management practices like herbicide use was found to have a significant positive effect on enterprise transformation. For example, farmers who adopted cross-breed cows reported higher milk yields and more stable daily income, enabling reinvestment into better feed, housing, and animal health services. Similarly, households using improved poultry breeds experienced increased egg production and more consistent cash flow, which accelerated their shift toward more commercialized poultry systems. In crop production, the use of herbicides reduced labor bottlenecks—particularly for weeding—and allowed farmers to expand cultivated areas or allocate labor to other income-generating activities, thereby contributing to broader transformation.

District-level patterns also emerged. Farmers in Ada'a Barga demonstrated more progress in transforming their enterprises compared to those in Bako Tibe, largely due to better infrastructure, greater access to input markets, and stronger linkages to urban consumption centers. Although mechanization and improved input use are gradually gaining traction across both districts, traditional practices still dominate many production decisions. Informal institutions and social networks continue to influence farm management, such as local norms around seed preservation that help mitigate seasonal seed shortages.

Despite land scarcity, farmers are actively diversifying their livelihoods, a strategy that supports incremental transformation. Overall, the study highlights those socio-economic, technological, and institutional factors operating at both household and district levels substantially shape the pace and depth of high-value enterprise transformation in the rural communities of central Oromia.

Based on the findings, the following recommendations are suggested for both farmers and agricultural development stakeholders:

- **Promote input intensification for higher-value enterprises**: Farmers should adopt strategies that maximize returns from limited land by integrating high-value crops and improved livestock breeds. This includes labor specialization, herd size reduction, and strengthening self-reliance in inputs. Stakeholders should support these efforts through targeted extension and resource monitoring.
- **Improve coordination among stakeholders and farmers**: Weak institutional coordination has hindered service delivery in the study areas, limiting farmers' access to inputs, credit, and reliable markets. Development actors should strengthen collaboration, build trust, and ensure accountability in service provision.

- **Enhance adoption of appropriate technologies**: While farmers recognize the limitations of traditional systems, the adoption of modern technologies remains slow due to issues of affordability, availability, and perception. Institutions such as the Ethiopian Agricultural Transformation Institute (ATI), Ethiopian Agricultural Research Institute (EIAR), and private agri-service providers should improve technology dissemination, revise extension strategies, and invest in farmer capacity building.

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Role of the Private Sector Participation in Transforming the Agribusiness Sector: Evidence from the Agricultural Trade and Investment Promotion (ATIP) project

Henok Mesfin, Aschalew Lemma*, Tsilat Yewondwossen and Mahlet Mekuria

Ethiopian Agricultural Transformation Institute (ATI), Agricultural Commercialization Clusters (ACC) Programme, P.O. Box: 708, Addis Ababa, Ethiopia.
*Corresponding author email: aschalew.lemma@ati.gov.et

Abstract

The Agricultural Trade and Investment Promotion (ATIP) initiative was implemented to stimulate agro-processing investment in Ethiopia by creating reliable demand channels and linking domestic agribusinesses to global food markets. The project also aimed to strengthen the investment ecosystem and enhance public sector institutional capacity to support quality private sector development. Analysis of project data and progress reports indicates that ATIP achieved significant milestones. Key accomplishments include the development of the food and beverage processing and auxiliary industries strategy in collaboration with relevant institutions, and participation in more than 15 domestic and international agrifood investment promotion trade fairs. The initiative also supported multiple capacity-building efforts to improve public sector effectiveness in attracting and facilitating private investment. In addition, branding strategies were developed for three priority value chains, and tailored support services were provided to domestic and foreign investors. A national soybean stakeholder alliance platform was established, with regular annual market linkage forums to strengthen coordination and market integration. The project further contributed to agribusiness development by facilitating initiatives that enhance private sector participation. As a result, investments exceeding 10 billion birr were mobilized, and market linkages worth over 5 billion birr were created. Import substitution was achieved in malt barley through vertical integration between smallholder farmers and breweries via out-grower schemes. Despite these successes, private sector engagement remains below potential, underscoring the need for continued interventions to foster a vibrant and sustainable market system that ensures lasting market access for smallholder farmers.

Keywords: Agro-processing, investment, market, private sector

1. Introduction

Investment in agro processing is crucial to the development of the agricultural value chain and a shift to a commercial agricultural model. Despite the agriculture sector being the largest employer and contributor to one-third of country's GDP, it is still at infant stage. In this regard, after conducting various surveys and discussions with local and international investors, several constraints were identified. Based on this, accessing investment-related information, limited support from the government to develop the sector, a lengthy/bureaucratic process to operationalize investment, forex shortages, delay in repatriation of profits, and issues in access to land/credit leading to limited investment in agro-processing. Due to this and other factors, investors wanted to get support in navigating the ecosystem, accessing information, reducing the red tape, and creating a link with smallholder farmers.

To this end, the Agriculture Trade and Investment Promotion (ATIP) project was designed to attract, engage, and convert strategic private sector investments in agri-business value chains and promote trade to create sustainable and reliable demand sinks for smallholder farmers, thereby improving the livelihoods and income of smallholder farmers in the Agricultural Commercialization Cluster. In addition, the project aimed to connect Ethiopia's agribusiness to global food markets, enhancing investment in agro processing, supporting technology transfer, employment generation and improving the overall investment ecosystem in the country. This has been done by advocating for the public sector and creating an enabling environment to improve policies and regulations to increase private sector investment in agriculture and strengthening public sector institutional capacity to support the operationalization of quality private sector investments in the sector.

To address these and other related issues, many interventions has been undertaken with strong collaboration and consultation with various public, private, and development partners. To mention some key partners, the Ministry of Agriculture (MoA), Ministry of Industry (MoI), Ministry of Trade and Regional Integration (MoTRI), Ethiopia Investment Commission (EIC), and their respective regional Bureaus. Furthermore, the Integrated Agro-Industry Parks (IAIPs) and Ethiopian Cooperative Commission (ECC), farmer organizations, agro-processors, etc. were major implementing partners.

2. Material and Methods

2.1. Project site and scope

The initiative was implemented for five years from 2020 to 2024 at the national level by collaborating with all levels of public, private, and development partners. The project focused on the Agricultural Commercialization Cluster (ACC) commodities associated with the Ethiopian Agricultural Transformation Institute (ATI) ACC woredas. Moreover, smallholder farmers, farmer organizations, commercial farms, agri-enterprises, and the private sector engaged in the agribusiness value chain are the key participants.

2.2. Operational Design and Implementation Approach

A highly consultative approach was followed by engaging key stakeholders from government, private, and development partners to improve the investment ecosystem and enhance exports. Ministry of Trade and Regional Integration (MoTRI), Ministry of Industry (MoI), Ethiopian Investment Commission, Ministry of Agriculture, Industrial Parks Development Corporation, Regional Agriculture and Investment Bureaus, Private Sector, trade and sectorial associations are key partners and stakeholders in the design and implementation of the project.

By its nature, the project has a broad base of participants starting from the smallholder farmers, commercial farmers, farmer unions, domestic and foreign agro-processing companies, and job-seeking youth. Also, the project has played a greater role in import substitutions and foreign currency generation. The participants were selected through continuous consultative discussion with stakeholders.

2.3. Data source and analysis

In preparing this paper, the project appraisal documents and five-year project

implementation progress report data were used as the primary sources for analysis and consolidation.

3. Results and Discussion

Investment pitch documents have been developed to promote the country's agribusiness potential in the international investment promotion events and to attract large-scale domestic and international private sector investment in the agriculture and agro-processing sectors. In line with this, nine international trade fairs and trade missions were co-organized, which generated a total export sales value of 260 million USD. These trade fairs and trade shows participated more than 350 groups of farmers and agribusinesses in the country. The initiative also facilitated inward trade missions for the East Africa Grain Council (EAGC), an association of grain, oilseeds and pulses producers, buyers, and processors from Eastern and Southern Africa. Based on this a full conversion process with a capital worth 10 billion birr investment has attracted, and many smallholder farmers have linked through out-growers scheme including malt barley producing farmers. On the other hand, through the promotion of Ethiopian agricultural commodities and creating market access a total value of more than 5 billion birr linked for more than 125,000 smallholder farmers in the ACC program which are linked to malt barley, avocado, sesame, soybean, maize and wheat supply for the processing industries.

3.1. Accelerating Investment in the Ethiopian Agro-Processing Sector

The Agricultural Trade and Investment Promotion intervention has been designed to convert promising investment opportunities by proactively targeting and engaging investors and addressing key systemic bottlenecks that currently restrict the growth of the private sector in agriculture. Many efforts have been made towards this objective. The Food and Beverage Processing and Auxiliary Industries strategy was developed in collaboration with the EIC and MoI to improve investments in the food and beverage processing sector and create market linkages for smallholder farmers. The strategy was socialized with all concerned stakeholders. The socialization was done through meetings and presentations at various forums, including the Regional Agro-Processing Forum to promote investment opportunities in Oromia, Amhara, and Tigray regions in collaboration with the regional investment bureaus, IAIPs, non-governmental stakeholders, and the private sector. Furthermore, regarding developing solutions for challenges inhibiting investments, has collaborated with the Foreign Economic Cooperation Centre (FECC) of the Ministry of Agriculture of the People's Republic of China focusing on the development of the Ethiopian beef and sesame value chains.

Efforts were made to accelerate the conversion of agro-processing investments and create a sustainable market linkage with smallholder farmers. To this end, theb project provided support to the full conversion process of large-scale domestic and international agro-processing investments in the country. Hence, agro-processing investments with capital worth 5.3 billion birr have been generated, and market linkage with smallholder farmers in ACC has been created. In line with this, the French Groupe Soufflet has invested 60 million Euros in Bole Lemi Industrial Park, and, Boort Malt has invested 50 million Euros in the Debre Berhan Industrial Park to build a malt processing factory through the support of the ATIP

project. The investments have created market linkage for more than 125,000 smallholder farmers who produce malt barley under the ACC program.

Figure 1. The 14th International Agriculture and Food Trade Fair (AGRIFEX), 2024, Addis Ababa

Figure 2. Soufflet Malt Ethiopia S.C factory establishment

Figure 3. Delegates from the Foreign Economic Cooperatio Centre (FECC) for the sesame and beef value chain

Figure 4: International Trade shows, Dubai

3.2. Promoting agricultural trade and market linkage

Agricultural trade and market linkage for agricultural commodities are also major issues identified to be addressed through this intervention by creating an enabling environment wherein smallholder farmers can have diversified opportunities to market their outputs and be effectively linked to local and global supply chains. Under this specific intervention, remarkable milestones were also achieved by designing and implementing different market strategies. Various works have been done to create both domestic and export market opportunities for smallholder farmers to market their outputs at better prices**.** This was done by accelerating and facilitating value chain alliances, linking smallholder farmers with off-takers through different marketing mechanisms: such as sales contracts, contract farming arrangements, vertical integration with agro-processing companies, and facilitating and co-organize different potential domestic and international market linkage platforms, such as exhibition, trade fairs, expos/showcases, facilitate business to business linkage forums and different inward and outward trade missions.

Ethiopia's Food and Beverage Processing and Auxiliary Industry Strategy was developed with a detailed market analysis and considered competitive factors for selected value chains and it was used as a tool for attracting agribusiness investments into the agri-food industry and linking them with smallholder farmers in the ACC. Accordingly, in five years of implementation, a market valued at 5 billion birr has been created for maize, teff, soybean, malt barley, wheat, and avocado commodities. The market linkage was facilitated through linking Farmer Production Cluster (FPC) farmers, farmer cooperative unions, and suppliers and processors, exporters, and institutional buyers such as the World Food Program (WFP) of wheat and maize supply for its humanitarian program; Ethiopian Industrial Input Development Enterprise for Soybean and Teff supply; Addis Ababa Consumer Associations for the supply of Wheat, Maize, and Teff participated as a buyer. To enhance the market viability of farmers and enter the export market participation, different strategic support has been provided, including certification of avocado-producing FPC farmers in the Oromia region, and farmers cooperatives in the Amhara region have received support in Global GAP certification. To achieve this, capacity-building training, business-to-business networking, as well as experience-sharing platforms have been facilitated, and 360 (42 women) smallholder farmers participated in the good agricultural practice certification procedure formal training.

Moreover, to meet international market requirements, a marketing brand was developed for Teff, Sesame, and Honey. Consequently, a brand called "Go Ancestorial" was developed with a promotional video and an implementation strategy, which has been handed over to the Ministry of Trade and Regional Integration (MoTRI) for further action.

To put in place a system that ensures sustainable market access for smallholder farmers, a soybean national market linkage consultative platform has been established. The soybean market linkage stakeholder forum has conducted regularly by the presence of high officials from concerned institutions and all supply and demand side actors. As a result through this initiative soybean market challenges become reduced, and processing companies can link with suppliers directly for input sourcing. In the 2024 forum only, more than 100 (16 women) participants drawn from federal and regional government bureaus, FPCs farmers from Amhara and Oromia regions, farmers' cooperative union from Amhara, Oromia, and Benishangul regions, edible oil processors, baby food factories, and animal feed processors have attended. Ultimately, a sales contract valued at 1.4 billion birr was signed between five farmers' cooperative unions and off-takers such as edible oil processors, animal feed processing companies, and Ethiopian industry inputs development enterprises.

The initiative has contributed and engaged in designing and implementing strategic interventions that address key bottlenecks of private sector development in agriculture and market access. To this end, the initiative supports the development of a contract farming proclamation, draft horticulture marketing directive, development of a cold chain plan, mapping of major horticulture fruits supply and development of a national storage strategy. Furthermore, the facilitation and organization of different stakeholder platforms, development of investment cases, etc. were major milestones that were achieved in support of the initiative.

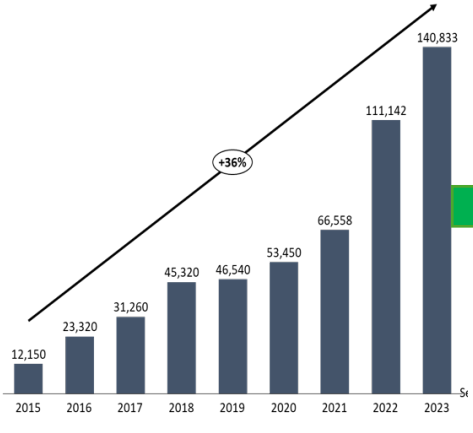
Figure 5: International Horticulture Expo-Addis Ababa Consultative Workshop

Figure 6: Soybean Value Chain

Figure 7. Branding the Value Chains

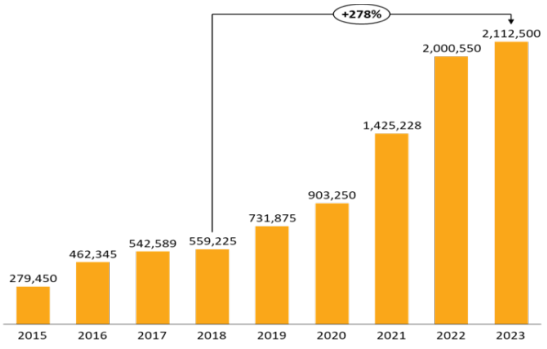
3.4. Key Success Story: the case of Oromia

Previously, Ethiopian beer factories sources malt barley input through importing from abroad. Due to the intervention implemented in collaboration with regional bureaus of agriculture and other institutions, a strong business partnership with beer factories and smallholder farmers and farmer cooperative unions was created through different market linkage approaches, such as contract farming and out-grower schemes created. As a result, the following success story was achieved.



As we can see from the graph, the number of farmers participated in the contract farming increases from 12,150 in 2015 to 140,833 in 2023. And it implies that it puts milestone to popularize the new approved contract farming approach which contribute to solve technical support, financial supply and input delivery. Because of this there has been a notable increase in the number of FPCs, farmers' participation, and the area dedicated to malt barley cultivation. To this end, the number of FPCs has increased by 10%, and the land area allocated through FPCs increased by 35%.

Figure 8. Number of farmers participating in contract farming
Source: Oromia regional malt barley initiative performance monitoring report



The supply of malt barley volume increase from 559,225 quintals in 2018 to 2.1 million which is by 278 %. Because of this, the amount of imported malt barley totally stopped. This has saved huge amount of foreign currency through import substitution.

Figure 9. The amount of malt barley supplied to malting facilities
Source: Oromia regional malt barley initiative performance monitoring report

4. Conclusion and Recommendations

The project achieved various milestones during its implementation period. Its contribution in the commercialization of the country's agriculture by strengthening the participation of private sector investment in agribusiness, promoting the sector's potential and creating market access for smallholder farmers was crucial. Furthermore, support has been provided for institutions to enhance their operationalization capacity and create good investment ecosystem by advising and developing policies and strategies as well as providing hands-on support service for investors. As a result of the initiative, investments valued over 10 billion birr were attracted, and a market valued over 5 billion birr was created through different market linkage strategies.

In the meantime, strengthening and incentivizing private sector development along the entire value chain is critical to transforming the country's agrifood industry. As the volume of marketable surplus continues to increase over time, the establishment of a vibrant, efficient, and inclusive market system becomes ever more vital. However, limited private sector participation in agriculture and constrained market access remain persistent challenges that require sustained and targeted efforts. Creating sustainable domestic and international market access, while enhancing private sector investment participation, therefore necessitates strong government support and coordinated engagement of all relevant stakeholders. In parallel, value addition at the farmer level remains a key bottleneck and calls for well-designed and context-specific interventions.

The establishment of a national soybean value chain platform has created an important opportunity to address market-related challenges while simultaneously increasing soybean production. The platform facilitates structured engagement between producers and buyers, enabling business partnerships and improving market linkages. Moreover, close collaboration with other project teams and relevant line ministries has enabled progress toward shared objectives with relatively modest budget allocations, demonstrating the value of coordination and synergy.

Furthermore, through the concerted efforts of the ATI and the project, and by working closely with stakeholders at all levels, international companies such as **Groupe Soufflet** and **Boortmalt** have successfully sourced malt barley locally. By engaging farmer producer cooperative (FPC) members through outgrower schemes, these companies were able to replace imports with domestic production, thereby meeting total demand locally and contributing to import substitution.

Investment promotion, by its nature, requires intensive participation in domestic and international trade fairs and investment forums, which often demand substantial financial resources, including foreign currency. Limited access to the required budget was a major constraint that reduced participation in a broader range of promotional events. Additional challenges included political instability, volatile market prices, contraband and illegal trade, and inadequate market infrastructure, such as the absence of cold chain systems.

In response, the program team prioritized engagement with domestic investors while also encouraging existing companies to expand and deepen their investments. With regard to participation in promotional trade fairs, the team worked closely with key government institutions, including the Ministry of Agriculture and the Ministry of Trade and Regional Integration (MoTRI), to mobilize resources and maximize joint participation, particularly in domestic investment promotion events.

In line with the above conclusions and identified challenges, the following key interventions are recommended.

- Strengthen support of the private sector development in agribusiness. Design and implement working procedures that encourage private sector investment.
- Organize and participate in international food market trade fairs to promote the country's agro-processing sector to attract potential investors.
- Strengthen vertical integration between agro-processing factories, smallholder farmers, and producer organizations through different strategies. Moreover, encouraging primary value addition activities at FPC and regional transformation centres (RTC) level and linkage with integrated agro-industrial parks (IAIPs).
- Strengthen the value chain governance and institutionalize the value chain alliances to solve key bottlenecks of the sector.
- Design and implement value chain-based financial products.
- Provide awareness creation training for youth (educated) on business opportunities in agriculture and support the sector in agri-tech (Digital market linkage platforms).
- Promote and implement the contract farming schemes and vertical integration of FPC farmers with agro-processing companies.
- Support the smallholder farmers in fulfilling the quality of international market requirements.

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Adoption of Study Findings for Project Development: Design and Implementation of Mechanization Service Centre Pilot Project

Zewdu Ayalew*, Samuel Keno, Awol Muhabaw, Dagnachew Lule, Gebre Gebretsadik and Henok Melaku.

Ethiopian Agricultural Transformation Institute (ATI), P.B.Box: 708, Addis Ababa, Ehiopia
*Corresponding Author: Zewdu.Ayalew@ati.gov.et

Abstract

The Ethiopian Agricultural Transformation Institute (ATI) conducted a comprehensive agricultural machinery service providers mapping survey and different pilot studies on mechanization services. The studies revealed that private and cooperative ownership models were favoured for machinery hire services catering to smallholder farmers. However, it is essential to address the risk aversion and lack of confidence shown by private service providers. Additionally, the survey highlighted that service providers face difficulties in obtaining maintenance services, quality spare parts, skilled operators, and qualified technicians necessary for their operations. Based on these findings and the national mechanization strategy, the ATI developed and implemented the Mechanization Service Centres (MSCs) pilot project. As a result, Nine MSCs have been established across three regions: four in Oromia, three in Amhara, and two in the former Southern Nations Nationalities Peoples Region. These Centers established with workshops and delivered mechanization services to 137,000 smallholder farmers. One MSC has successfully created connections for the sale of spare parts, yielding an income of 2 million Birr. These outcomes serve as compelling evidence of the MSC project's success and offer valuable insights into the effective translation of research findings into comprehensive project development. Nevertheless, MSCs have not fully started all ancillary services to their maximum potential. Additionally, certain MSCs lack sufficient agricultural machinery, which hinders their ability to offer complete services with full potential to assess the effectiveness of the model. So, it is advisable for the ATI to maintain its support for MSCs and ensure that their operations meet the standards established in the project design.

Keywords: Agricultural machinery, Mechanization, Service delivery models, Service providers, Maintenance service

1. Introduction

Agricultural mechanization, which applies engineering principles to agriculture, is frequently employed to improve the efficiency and productivity of human labour (FAO and UNIDO, 2008). Although it significantly contributes to the national economy's growth, the current use of agricultural mechanization in Ethiopia remains limited, especially among smallholder farmers. The heavy dependence on manual labour and animal power has resulted in low production and productivity within the agricultural sector. Therefore, implementation of advanced mechanization techniques is vital.

The Ethiopian Agricultural Transformation Institute (ATI) has identified agricultural mechanization as a key area for intervention and supported the development of National Mechanization Strategy. Besides, it undertook various studies, assessments, surveys, and implemented pilot projects as preliminary measures to have cohesive solutions. A comprehensive survey has been conducted to map agricultural machinery service providers

(Gebre and Samuel, 2022). Similarly, the Institute undertook a pilot study on mechanization services, which sought to determine the most effective ownership model for delivering mechanization services and uncover the underlying reasons for the limited investment in mechanization service provision within the country (Temesgen and Legesse, 2014). The primary aim of these studies was to identify challenges, define effective pathways and formulate potential solutions to overcome these obstacles. The findings clearly demonstrated that private and cooperative ownership models are favoured for the provision of farm machinery hire services. It was also noted that it is essential to address the risk aversion and lack of confidence among private service providers. Additionally, the results revealed that mechanization service providers face challenges in accessing maintenance services, quality spare parts, skilled operators, and qualified technicians.

Considering these results as well as the methodologies proposed by the National Mechanization Strategy, ATI developed and implemented the MSC pilot project with primary objective of creating better access to modern machinery for smallholder farmers. Additionally, the project was intended to provide short-term training in mechanization, provide machinery maintenance services, and the supply of authentic spare parts. By these, ATI tried to address several problems identified during the studies.

Nine Mechanization Service Centers (MSCs) have been set up across three regions. These Centers have provided mechanization services for a total of 137,000 smallholder farmers. Besides, machinery fleet of these MSCs expanded, functional maintenance workshops have been setup, and one MSC started sales of quality spare parts. Such results showed that MSC approach can help mitigate identified problems.

However, due to various reasons, the majority of MSCs were unable to provide all ancillary services at their full capacity. Furthermore, most MSCs are not adequately equipped to provide comprehensive mechanization services. Hence implementation of the MSC project is incomplete, and the effectiveness of the proposed model is yet to be evaluated. It is, therefore, recommended that ATI should continue its support for MSCs to enable them to implement comprehensive mechanization services as outlined in the project design. Establishing collaborative partnerships with other governmental and non-governmental organizations may also be crucial in providing support to MSCs.

This paper briefly discussed ATI's approach, utilizing findings from various studies as a stepping-stone for the development and implementation of MSC project, which will have a wider impact and applicability for years to come.

2. Materials and Method

2.1. Description of implementation sites:

The project was designed to be implemented in four major ATI intervention regions. Four Zones in Oromia, three Zones in Amhara, two Zones in the former SNNPR and one Zone from Tigray Region were selected (Table 2). However, the project in Tigray region was discontinued due to security related concerns. The project was implemented only on nine sites.

2.2. Development of MSC pilot project design

The results obtained from earlier ATI studies including the 'Agricultural Mechanization Service providers mapping survey', the 'Examination of Small-Scale Thresher Business Models', the 'Mechanization Pilot Study', and the 'National Agricultural Mechanization Strategy (NAMS)' were employed to pinpoint challenges, suggest recommended models, and develop a thorough project concept.

Following the examination of the survey results and the conclusions drawn from various pilot-level mechanization studies, ATI developed the project design for the MSCs pilot. The insights gained from these studies, along with supplementary pilot-level research, have been instrumental in the project's development. After the project formulation, it was evaluated in several forums, refined as necessary, and subsequently received approval for national implementation.

A private consultant has been engaged to create a detailed design for civil works. This design was developed based on a comprehensive list of technical specifications identified as customer requirements. The Institute has assembled this guide and design developed thereby. The final design for all civil structures has undergone rigorous assessment in various forums and has integrated feedback from stakeholders before its finalization and approval.

2.3. Project sites and MSC operators' selection

A decision was reached to create a total of 10 Mechanization Service Centers (MSCs) for pilot testing purposes. The chosen implementation areas were intentionally selected, focusing on the four primary agricultural production regions, which are also the key intervention areas of ATI: Oromia, Amhara, the former SNNPR, and Tigray. The specific zones for the establishment of MSCs were determined in accordance with recommendations from the regional Bureaus of Agriculture. The criteria for selection included, but were not limited to, the presence of Farmer Producer Clusters (FPCs) in key crop commodities, agricultural production capacity, suitability for mechanized farming, accessibility, and various crop-related considerations.

The process of identifying the most suitable operator for MSC establishment involved a comprehensive selection procedure. Announcements inviting businesses deemed potential MSC operators were circulated through various channels and displayed in key zonal and woreda towns. A workshop was held to brief participants, during which all necessary documentation and information were shared with the applicants. The application process and requirements were explicitly detailed. Attendees received support on developing business proposals, crafting business plans for mechanization services, and addressing other important topics. A technical evaluation panel, consisting of representatives from various stakeholders, was formed to facilitate the selection of the most qualified bidder. In the end, a due diligence assessment was performed at the head office level. It was aimed to evaluate whether a sub-recipient, specifically the chosen MSC operator, has the necessary capacity and systems to execute ATI's sub-grant in compliance with the stipulations set forth by ATI and the relevant donor.

2.4. Data collection and analysis

Descriptive research method was employed to conduct the survey part, as it is often considered as visual aid. Word cloud generator has been used in summerizing keywords provided by all respondents concerning challenges related to operators. Construction progress as well as service provision status of each MSC was collected manually on a quarterly basis. Besides, project monitoring technical team has been deployed at each MSC level to closely support and monitor implementation. Furthermore, field visit was conducted by the monitoring and evaluation team from ATI and its stakeholders. Two MSCs, Melik and Damota, were sampled and included in the assessments to measure the MSCs functions. The quality of services provided, and the satisfaction levels of beneficiary farmers were evaluated using established monitoring and evaluation methodologies.

3. Results and Discussion

The Agricultural Mechanization Service Providers Mapping Survey revealed that there were about 696 agricultural machinery service providers in the surveyed regions. However, given the production capacity and the appropriateness of the surveyed areas for mechanization, this number is insufficient to meet the mechanization demands of all smallholder farmers in this high-production context. Furthermore, the distribution of service providers is not uniform across the regions.

Word cloud generator has been used in summerizing keywords provided by all respondents concerning challenges related to operators. The resulting visualization, illustrated in Figure 1, reflects the intensity of the issues based on their visibility. Larger text signifies the most frequently mentioned concerns. From these discussions, the primary challenges recognized as the most prevalent were scarcity of machine operators in the market and lack of skill for machine operators.

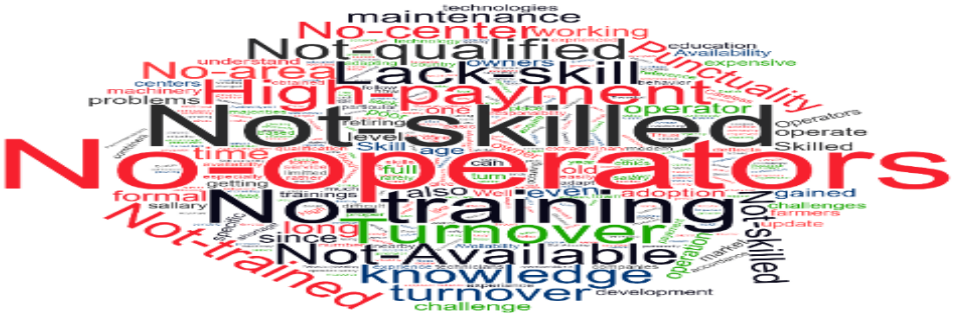


Figure 1. Summary results of machinery operator related problems.

When service providers were asked about accessibility of maintenance and repair services, more than 50% of the respondents indicated that they didn't have access for regular machinery repair and maintenance services (Figure 2A). Likewise, regarding availability of skilled technician for repair and maintenance services, around 72% of the respondents (Figure.2B) indicated that there was no skilled technician/mechanic to properly diagnose and give rapid solution for machineries related problems.

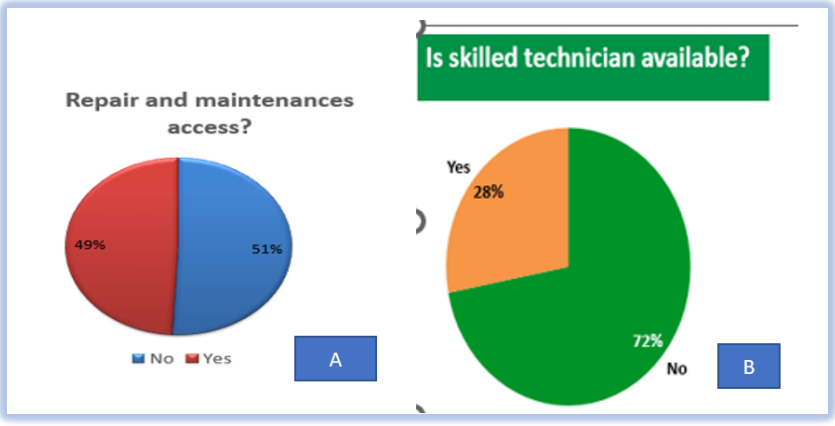


Figure 5. Availability and accessibility of repair services and technicians.

Similarly, survey findings indicated that approximately 88% of the respondents (Figure 3A) lacked access to machinery spare parts in local stores, while only 12% reported having better access. Furthermore, 42%, 33%, and 28% of service providers obtain spare parts from zonal, regional, and national capitals (Addis Ababa), respectively, which are often far from service areas. Only 26% of the respondents indicated that they could acquire spare parts from nearby maintenance shops.

A similar observation was made indicating that approximately 55% of the respondents experienced quality-related issues with the spare parts they purchased. Concerning the pricing of machinery spare parts, 90% of the respondents expressed that the costs they incur for these items are excessively high. In contrast, only 10% of the respondents considered the prices to be reasonable.

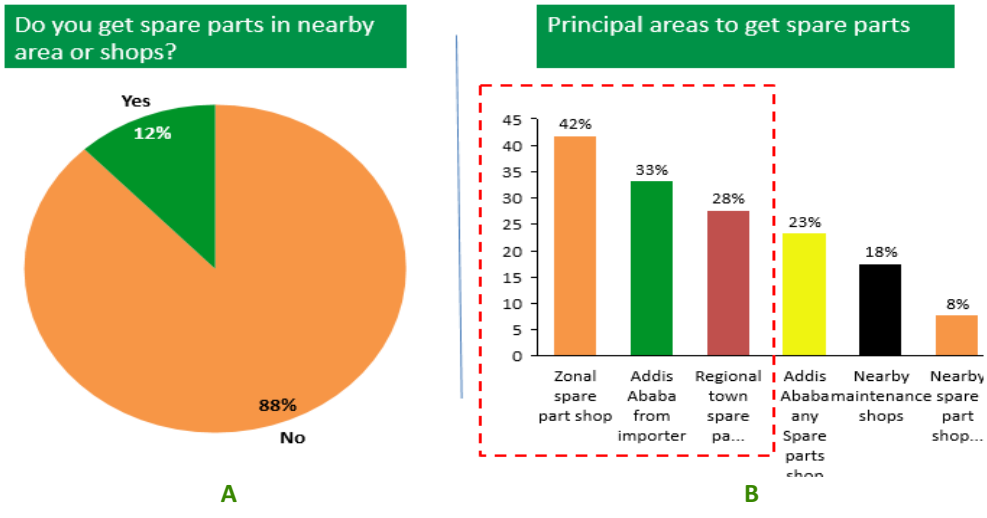


Figure 6. Responses for availability and location of Spare part supply

The overall findings of the survey results revealed that most mechanization service providers struggle to find skilled machinery operators in the market, and there were no operator training centers located in their vicinity. Additionally, they face difficulties in obtaining repair and maintenance services, as maintenance facilities are also lacking in nearby areas. Furthermore, spare parts are not readily available, necessitating that service providers travel to zonal, regional, and capital cities to procure these components. Service providers lack the expertise to identify quality spare parts, as they often procure them from outside their locality without the assistance of technicians. The elevated prices of spare parts adversely affect farmers by raising the overall cost of services.

3.1. Implementation of study findings for MSC project design

Comprehensive MSC Pilot project has been developed fundamentally grounded in the findings of several ATI studies. These include: Mechanization Pilot Study, the Machinery Mapping Survey, and the National Agricultural Mechanization Strategy.

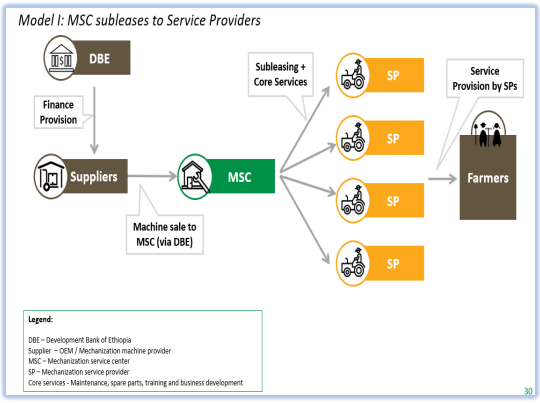
The National Mechanization Strategy has explicitly stated that a significant portion of the farming community falls under the smallholder farmer category. Therefore, the project's primary objective should be addressing the mechanization requirements of smallholder farmers. It has also been concluded that an organized service provision model is more effective than individual ownership of machinery (National Mechanization Strategy, 2014). Furthermore, findings from the pilot ownership study suggest that the service should ideally be managed by cooperatives or private entrepreneurs and service providers (Table 2).

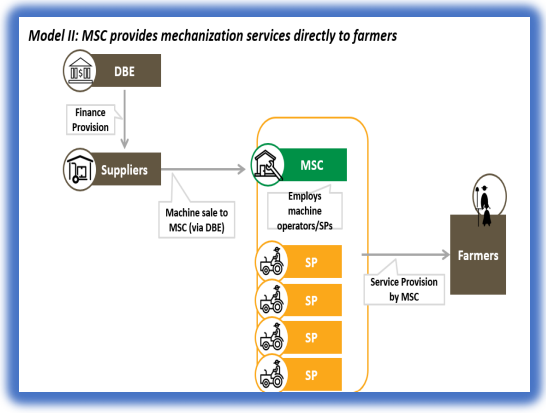
Likewise, insights gained from the 2016 Mechanization Pilot Study led to the inclusion of support packages designed to encourage substantial investments in the mechanization sector and to tackle key issues identified by service providers. These incentive packages encompass access to capital, high-quality machinery to minimize failures, maintenance and spare parts availability, and quality training. Moreover, as indicated by the results of the SP mapping survey, the project design has adopted an integrated approach to deliver various support services for the sustainable provision of mechanization services. Consequently, the following key findings from earlier studies were integrated into the development of the MSC project:

The project design proposed two primary methods for delivering MSC services (Figure 4). It showed the source of finance, suppliers' role and service provision approaches for smallholder farmers. The decision regarding which approach to adopt was left to the decisions of the regional bureaus of agriculture and the MSC owners. Ultimately, all stakeholders and MSC operators opted for option B (figure 4.), leading to the implementation of this service provision method across all MSCs.

Table 3. Adopted ideas for project development of pilot MSCs.

No	Project idea/ recommendations	Source of information	Application in MSC project
1	Addressing machinery needs of smallholder farmers through mechanization service provision	The National Agricultural Mechanization Strategy and other related studies	Establishment of MSCs whose primary objective is creating access for Mechanization service for SHF
2	Ownership by cooperatives/ private entrepreneurs	Pilot study in machinery (thresher) ownership business model	Cooperatives and farmer entrepreneurs were preferred to own/operate MSC
3	Provision of mechanization services for all field operation	Agricultural Machinery Service Providers Mapping Survey	Plan includes End-to-end mechanization services provision by MSCs
4	The need for having well-equipped maintenance and repair services	Agricultural Machinery Service Providers Mapping Survey	Including maintenance and repair service as a component under MSC
5	The need for enhancing accessibility and quality of machinery spare parts for service providers	Agricultural Machinery Service Providers Mapping Survey	MSC design includes provision of genuine spare part as one o the MSC functions
6	The need for availing training service to capacitate machinery operators and others in mechanization value chain	Agricultural Machinery Service Providers Mapping Survey	MSC design includes provision of an accredited training program for Operators and Technicians
7	The need for including incentive packages to private service providers' risk aversion and lack of confidence	Mechanization service pilot project	MSC project incorporated incentive packages for MSC operators including subgrating 70% construction for civil structures, operators supported with having access for credit finance, granted with land for placement of civil works





A **B**

Figure 4. Two possible service provision approaches suggested by the design team.

3.2. MSC pilot implementation

The execution of the MSC project has facilitated the creation of Mechanization Service Centers in strategically chosen locations. As a result of these initiatives, the construction of eight MSCs has been successfully finalized: four in Oromia, three in Amhara, and one in the Central Ethiopia region. Additionally, the construction of one MSC in the Wolayeta zone, which is currently 67% complete, remains to be finished. Furthermore, the construction of another MSC in Tigray has been halted due to security issues in the area designated for its development.

Table 2. List of MSCs established, selected owners, location, and construction status.

Region	Name of MSC	MSC owner	Zone/location	Remark
Oromia	Sikomando MSC	Sikomando FCU	Bale	Completed
	Galema MSC	Galema FCU	Arsi	Completed
	Ambo MSC	Ambo FCU	West Showa	Completed
	Gibe-Dedessa	G. Dedessa FCU	East Wollega	Completed
Amhara	Bure Damot MSC	Bure Damot FCU	West Gojam	Completed
	Gozamin MSC	Gozamin FCU	East Gojam	Completed
	Mandela Temesgen (Metema) MSC	Mandela Temesgen (Private)	West Gonder	Completed
SNNPR	Melik Silte MSC	Melik Silte FCU	Worabe	Completed
	Damota MSC	Damota-Welayeta FCU	Wolayita Sodo	Not completed

All the MSCs adopt similar civil structure design which is composed of the following main components:

Office or administrative building - This facility occupies a floor area of 29 x 20 m² and consists of eight rooms, including two training rooms, a meeting room, various administrative offices, an assembly hall, a staff cafeteria, showers, toilets, and other related amenities. It features a reception area, a veranda, landscaped green spaces, and additional utilities designed to foster a conducive working environment for both staff and clients.

Machinery maintenance workshop - This workshop is a critical component of the MSC, serving as the primary location for machinery maintenance activities. Spanning approximately 43 x 17.2 m², it included around 13 rooms, such as a machinery shop, a welding and machinery area equipped with workbenches, a spare parts warehouse and sales room, offices, shower facilities, and other necessary structures, all organized efficiently. Additionally, it contains a maintenance pit for conducting inspections and maintenance services.

Machinery sheds - Protecting machinery within dedicated sheds is essential for ensuring their safety and prolonging their operational lifespan, while also minimizing maintenance expenses. Consequently, each MSC is equipped with two such shelters, with floor areas of approximately 66 x 11 m² and 48 x 11 m², capable of accommodating over 17 large machines simultaneously. These shelters are primarily designed for tractors and combine harvesters but can also house other types of machinery.

Generator house - This facility is designated for the installation of a standby power generator, which serves as a backup during interruptions in the main electrical power supply.

Other structural components - The MSCs are equipped with various other essential structures, including guardhouses, machinery washing pit, fire extinguisher systems, tire maintenance area, septic tanks and other critical electrical and sanitary installations.

These structures are fundamentally needed for implementation of the four MSC functions: mechanization hire service for farmers, provision of short-term training in mechanization, maintenance and repair of farm machinery, and sales of spare part for service providers.

Figure 5. Overview of MSC plan and one of constructed workshops in MSCs

3.2.1. Agricultural mechanization access created by the services centers

Fragmented land holding and the excessive costs associated with machinery ownership pose significant challenges for individual farmers looking to use large equipment on their farms. The

Fee-for-Service model, facilitated through MSC, is expected to enhance access to machinery for the extensive population of smallholder farmers.

Throughout their construction phase, all nine MSCs have actively provided fee-based mechanization services, focusing primarily on land preparation, and harvesting. Over time, they have expanded their service offerings to include secondary tillage, chemical spraying, harvesting, threshing, and transportation, using advanced machinery. During the project implementation period from 2019/20 to 2024, nine functional MSCs supported over 137,000 smallholder farmers with access to Mechanization services. Furthermore, the annual service provision capacity of MSCs increased significantly, from serving 5,392 farmers in 2019/20 to more than 46,350 farmers by 2023/24, as reported in the ATI annual reports. This growth is a substantial improvement in access to mechanization services for smallholder farmers. This showed an average growth of about 8100 smallholder farmers annually. This implied that more farmers are progressively convinced to use mechanization services, recognizing the real benefits of using modern machinery. If such trend is kept for the coming years, it will have the desired impact on smallholder farmers access for mechanization.

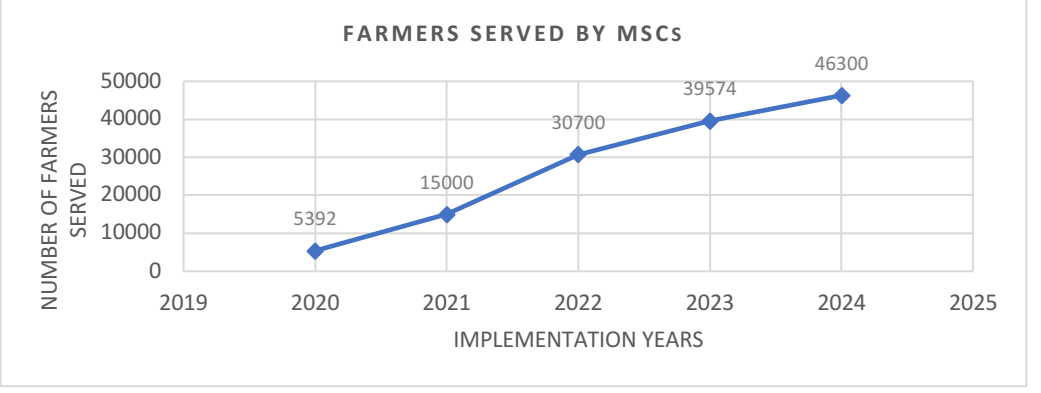


Figure 6. Annual progress of farmers served by MSCs

A field visit conducted by a team composed of Monitoring and Evaluation team from ATI and its stakeholders showed that two MSCs, Melik and Damota, were sampled and included in the assessments to measure the MSCs functions. The quality of services provided, and the satisfaction levels of beneficiary farmers were evaluated using established Monitoring and Evaluation methodologies. The findings showed that the smallholder farmers interviewed expressed a prominent level of satisfaction with the services offered by the MSCs, scoring 4.25 points, and with the timeliness of service delivery, scoring 4.5 points (Figure 7). These favorable outcomes may have contributed to the observed increase in the number of farmers served (Figure 6).

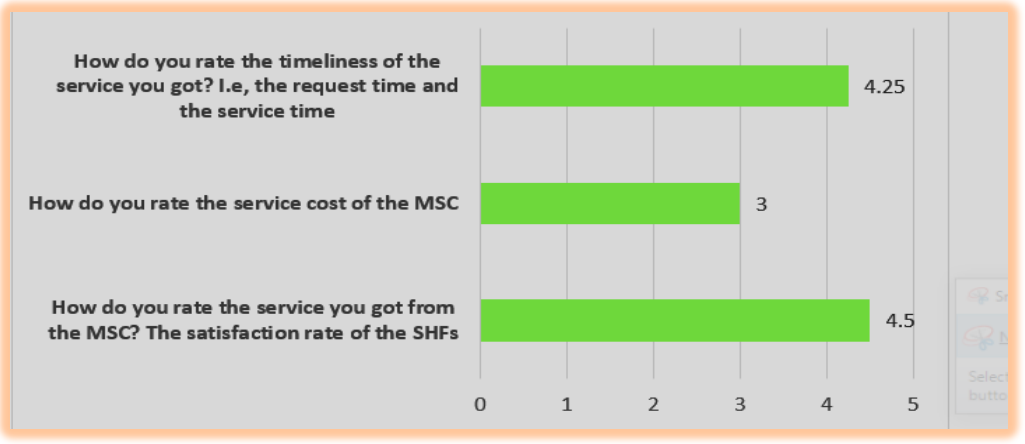


Figure 7. Evaluation scores by farmers (5 pt. Maximum) MSC service provision states

3.2.2. Increased access to good quality machinery for MSC function

The effectiveness of the MSC model hinges on the ability of MSC operators to get and effectively use high-quality machinery within a sustainable business framework. However, despite the efforts made, the lease financing arrangement with Development Banck of Ethiopia was not successfully implemented. Hence MSCs were forced to explore other alternatives to expand their fleet of machinery and increased the range of services they offer. The following machinery were acquired by the MSCs:

1. Six MSCs purchased 13 combine harvesters and 26 tractors through lease financing and other financial arrangements, from private banks and other lending institutions, and some from one machinery leasing company (Ethio-lease).
2. The Ministry of Agriculture distributed 30 equipment and machineries for seven MSCs (Bure, Gozamin, Mandela T., Galema, Gibe-Dedessa, Ambo, and Melik).
3. The ATI distributed different seed drillers for selected service providers in Teff and Wheat clusters, of which five were given for five MSCs.

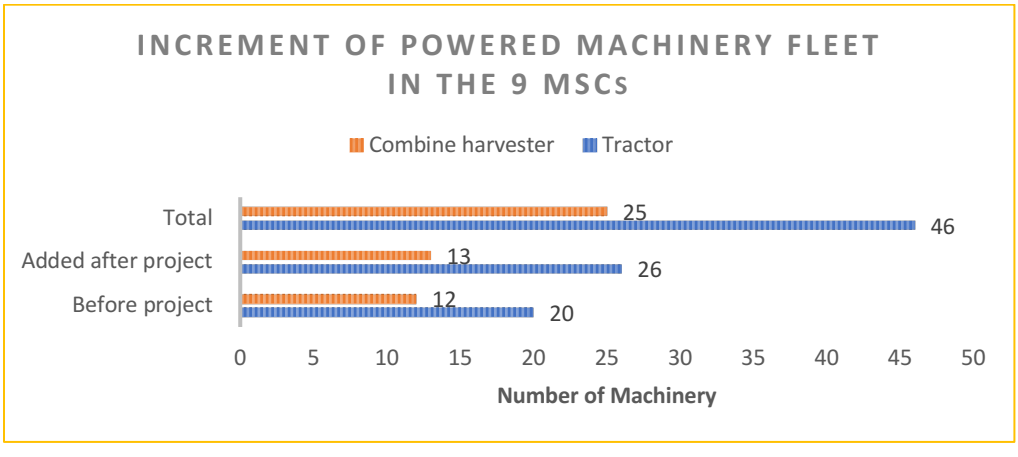


Figure 8. Number of Machinery fleet after MSC establishment

3.2.3. Strengthened capacity of service provider through ancillary services

To enhance the service provision capabilities of both the Mechanization Service Centers (MSCs) and local private machinery service providers, the project has implemented essential technical training programs aimed at improving the quality of machinery services available to farmers. Approximately 81 operators of machinery, including tractors and combine harvesters, underwent training in machinery operation and some of them obtained driving licenses. Additionally, 27 technicians received training in machinery maintenance to enhance their qualifications as machinery technicians. Moreover, over 60 MSC managers took part in training focused on farm machinery business management. These capacity-building initiatives improve the accessibility and operational efficiency of machinery, leading to an increase in overall machinery availability. This may have contributed to an increased number of smallholder farmers accessing mechanization services.

3.2.4. MSC ancillary services

As clearly observed from earlier studies, availing machinery without ancillary services could be a liability rather than an opportunity. Hence, the MSC pilot project has given due consideration and incorporated services in machinery maintenance, mechanization training and spare part sales.

3.2.5. Functionalizing maintenance and repair service

Established MSCs are tasked with operating machinery maintenance services for both their own equipment and that of nearby service providers. To effectively operate these maintenance services, MSCs require a comprehensive set of tools and machinery. The ATI collaborated with GIZ for the delivery of over 100 sets of workshop tools for each MSC. By utilizing these resources, and supplementing them with their own assets, most MSCs have commenced machinery maintenance and repair services, as evidenced by the results presented in Table 3.

3.2.5.1. Starting short-term training programs

Established MSCs are tasked with provision of short-term trainings mainly for machine operators and technicians for other mechanization service providers. To initiate the training program in MSCs, consultative and planning meetings have been held with relevant stakeholder institutions, resulting in the creation of a comprehensive proposal document. This document outlines the proposed training curriculums and identifies beneficial training topics. Additionally, it includes a list of necessary materials for setting up the training centre and provides estimates for the approximate budget required. The human resource needs for establishing the training unit have also been assessed. The document is now prepared for final evaluation and approval by stakeholders.

However, it was noted that establishing training centres for giving accredited training programs in mechanization requires the availability of several machineries and materials for practical training. This demands a huge sum of money, which the owners are unable to secure currently. This will be an issue to be addressed by stakeholders and may need the attention of actors for years to come.

3.2.5.2. Supply of spare parts for farm machinery

All MSCs are required to supply the necessary spare parts for agricultural machinery and maintain an adequate inventory to minimize maintenance delays. To initiate this service, each completed MSC has established a warehouse specifically designed for the storage and sale of spare parts. Additionally, one MSC, Mandela Temesgen, has successfully formed partnerships with machinery importers and spare parts suppliers, and has commenced the delivery of genuine spare parts within its operational area. Table 4. presents the sales volumes of spare parts and machinery over the past year, along with the corresponding revenue generated by Mandela Temesgen MSC.

Table 4**.** Functionality and number of machineries serviced by MSC workshops.

No	***MSC***	**Functionality of Maintenance Workshop**	**# of machineries Repaired**				
			Tractors	**Combine Harvesters**	**Other machineries**	**Total**	**Remark**
1	*Ambo*	*Yes*	14	1	--	15	For own machine
2	*Sekomando*	*Yes*	2	4	--	6	For own machine
3	*Galema*	*Yes*	5	6	--	11	For own machine
4	*Gibedidessa*	*Yes*	7	NA	--	7	For own machine
5	*Gozamin*	*Yes*	1	4	3	8	For own machine
6	*Damot*	*Yes*	10	2	23	35	For own machines
7	*Mandela T.*	*Yes*	22	NA	64	86	own and others
8	*Melik*	*Yes*	2	1	1	4	For own machines
9	*Damota*	*No*	NA	NA	NA	NA	
	Total		63	18	91	172	

In addition, the ATI collaborated with stakeholders and the MSCs to develop a proposed organizational structure, including the preferred organogram for operating MSCs at full capacity. The necessary workforce, along with their qualifications and experience levels, has been identified, and comprehensive job descriptions have been created and shared to MSCs for adoption.

Table 5. Machinery spare parts supply data by Mandela MSC

S/N	Agreement Signed with Private Company	Spare Items	Spare Part Sales By Mandela Temesgen MSC				
			Kinds of spare parts supplied	# sales	Sales Year/ EC	Revenue obtained, (ETB)	Remark
1	MAMEY plc	1	Thresher spare parts	78	2015/16	1,184,000	
		2	04- & 05-disc plow	4	2015/16		
		3	disc harrow 28 discs	1	2015/16		
		4	Row Planter, Multi type, 28 row	1	2015/16		
		5	Boom sprayer 600 Lit	6	2015/16		
		6	Local plow	4	2015/16		
2	Rice En. Plc	1	Engine spares, d/t items	50	2015/16	270,000	
		2	Dinamo	3	2015/16		
		3	Moterino	6	2015/16		
3	Woreta In. Business Group	1	Filtero	42	2015/16	194,201	
		2	Hydraulic, and Fuel pump	3	2015/16		
		3	Dinamo	4	2015/16		
		4	Moterino/ ሞተሪኖ	8	2015/16		
		5	Belts	8	2015/16		
		6	Tire with KALAMADERIA	14	2015/16		
4	Bezuayehu Trading	1	Different gears	6	2015/16	261,884	
		2	Engine spares, d/t items	18	2015/16		
		3	Dinamo	4	2015/16		
		4	Moterino/ ሞተሪኖ	6	2015/16		
		5	Different size tire	14	2015/16		
		6	Plow Bearing	68	2015/16		

4. Conclusion and Recommendations

The MSC project was designed to enhance smallholder farmers' access to farm machinery services. The project implemented a study findings-based project development approach, which has incorporated relevant study findings to solve pertinent problems. Evidence indicated that it has been successful in this regard. The number of smallholder farmers who received mechanization services has risen significantly, with an annual increase of 1,800 farmers, culminating in a total of 137,000 over a five-year period. Maintenance and servicing of machinery improved across all MSCs, with the total number of machines maintained exceeding 340. Additionally, efforts to sale spare parts at one of the MSCs led to increased revenue for the MSC operator and facilitated easier access for service providers in the surrounding area. However, the full impact of the MSC project is yet to be realized due to certain missing components from the expected standards.

Despite these challenges, the project has made a meaningful contribution to one of the ATI objectives by establishing well-designed, multifunctional MSC civil structures at the point of use. This has aided in the development and rollout of a sustainable mechanization supply chain and service provider business model aimed at reaching various segments of farmers.

Moreover, with appropriate actions taken to optimize the functionality of the established Centers, the MSC framework created by the project has the potential to effectively tackle the systemic bottlenecks identified in the agricultural mechanization strategy.

The establishment of a well-equipped and operational center, along with a functional training unit within the Mechanization Service Centers (MSCs), can significantly improve farmers' understanding of mechanization. The proposed methods of sub-granting, lease financing, and machinery leasing can be applied to other comparable regions, addressing financial gaps that hinder the adoption of mechanization. Additionally, the presence of a functional spare parts sale's unit within MSCs can effectively address a critical challenge in mechanization: the scarcity of spare parts and after-sales services. Furthermore, these established centers can function as demonstration sites and serve as efficient distribution models for agricultural technologies.

The following recommendations are generated from learnings during few years of implementation.

- The machinery rental sector should expand its offerings by providing a variety of machinery services tailored for different agricultural operations. Additionally, all ancillary functions of MSCs should be started.
- It is strongly advised that the project be directed towards full implementation for at least one more year, followed by an evaluation based on the established pilot assessment criteria.
- The MSCs should be equipped with both machinery and essential office and training facilities as soon as possible.
- The MSCs should be encouraged to adopt or modify the proposed organizational structure.
- The MSCs ought to provide comprehensive mechanization services, allowing farmers to implement mechanization throughout the production process, from land preparation to transportation and storage.
- All MSCs, particularly the top-performing ones, should receive guidance in establishing adequately equipped training centers and supported in obtaining legal recognition or certification.
- The MSCs should establish connections with major machinery suppliers and spare parts importers. It is crucial for MSCs to be effectively linked and integrated with extension services. A viable market for the services provided is essential, and all Farmer Producer companies (FPCs) should utilize mechanization services to modernize their agricultural practices.
- Conducting a terminal evaluation is vital, and findings together with the insights gained should be shared for project long term owners.
- It is essential to reassess construction design and procedures. A review of lessons learned regarding construction procedures (standardization), supervision methods, and other pertinent issues is necessary.
- MSCs can facilitate access to mechanization for smallholder farmers, even in the most remote areas of the zone. Therefore, any new initiative to establish an MSC should carefully consider the optimal locations for introducing these technologies.

- The promotion and implementation of the ACC approach, which supports commercial agriculture, are vital for the effective application of mechanization within the MSC framework. Establishing connections and networks between FPCs and MSC services is crucial.
- In contrast to cooperative-owned MSCs, privately owned MSC demonstrated significant differences in project execution and the management of grants and contracts. Additionally, it led the way in exploring various MSC strategies for implementing new service areas

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The Contribution of Farmer Production Clusters to the Commercialization of Smallholder Farmers: Key Achievements of Grain Farmer Production Cluster Project

Megersa Debela*, Weyessa Garedew, Dagnachew Lule, Kassa Yihun, Zerihun Abebe, Kindie Aysheshm, Teshome Walle, Desalegn Duguma, Mulugeta Fetene, Germame Garuma, Abreha Kidanemariam, Basazinew Mohammed, Birhanu Mentafa, Debebe Gashawbeza, Tadesse Teweldebirhan

Ethiopian Agricultural Transformation Institute , Agricultural Commercialization Clusters Program, Ethiopia
*Corresponding author: megersa.debela@ati.gov.et

Abstract

The Grain Farmer Production Cluster (FPC) project was launched under the Agricultural Commercialization Clusters (ACC) program aiming to increase the production and productivity of the six priority grain commodities: wheat, maize, teff, malt barley, sesame, and soybean. The grain FPC project was launched to be implemented in 300 selected woredas, grouped into 31 geographic commodity clusters across seven regions. The overall progress of the project indicated that there was significantly enhanced input utilization, production, productivity (3.26 tons/hectare), and marketable surplus as well as participation of smallholder farmers in producing priority commodities in cluster. Originally planned to organize 62,500 farmer production clusters, the project has surpassed expectations and was able to engage >99,000 clusters with over 2.4 million farmers covering 1.99 million hectare. Total grain production volume reached 83.2 million quintals, exceeding the initial year's 25.3 million quintals and marketable surplus volume reached 35 million quintals, representing a 62% surplus share. Efforts were also made to encourage on-farm storage, primary processing, and infrastructure development, with model FPCs receiving support in farm equipment and infrastructures. Despite significant progress in various project metrics, areas requiring improvement include addressing the productivity of sesame crops, enhancing farmer access to financial institutions for credit, and ensuring effective transitions for FPCs into companies. Legalizing FPCs and focusing on their succession through strategic planning are crucial for sector improvement. Expanding interventions across different agroecologies and commodities, along with reinforcing the Farmer Production Company model, will be pivotal for advancing agricultural commercialization and sustaining the project's success.

Keywords: Market, Priority commodities, Productivity, Surplus production, Value Chain

1. Introduction

The agriculture sector plays a crucial role in the Ethiopian economy, contributing significantly to both the GDP and exports. Currently, it accounts for 32% of the country's GDP and a remarkable 75% of its exports (NBE, 2023). However, this sector has been facing significant challenges, primarily stemming from low productivity. The main reason behind this low productivity has been the continued reliance of smallholder farmers on traditional and outdated farming practices that are no longer sustainable in today's context. Recognizing the need to address these challenges, Ethiopia has established a nationwide agricultural extension system. The overarching vision of this system is to create a market-led and pluralistic extension framework that enhances the lives and livelihoods of smallholder

farmers, agro-pastoralists, and pastoralists in the country. Among the various approaches adopted by this extension system, one notable strategy involves promoting the adoption of Full Package Recommendations.

The Full Package approach emphasizes optimal inputs and tailored agronomic protocols for each agricultural commodity. Despite various efforts to promote it, adoption among farmers remains limited due to lack of awareness, inadequate input supply, limited extension agent capacity, and poor market access. In January 2018, the Ethiopian Agricultural Transformation Institute (ATI) launched the Accelerated Full Package Scale-up (AFPS) project to address these issues holistically, focusing on farmer-level interventions and clustering farmers to enhance operations and agronomic practices. The project showed initial positive outcomes, with increased acceptance of recommended practices and productivity improvements. However, evaluations results have revealed gaps, including misalignment among stakeholders, insufficient integration of interventions, capacity issues within the implementation team, and inadequate project documentation.

Based on these evaluation findings, the project conducted a comprehensive analysis of the challenges faced during the 2018/19 implementation years. Additionally, international case studies were reviewed to extract valuable lessons and insights for the project's redesign. With ambitious growth targets and ongoing support, the AFPS project was restructured and renamed the Grain Farmer Production Cluster (FPC) project. This new initiative built on the lessons learned and aimed to address the challenges identified in the prior project implementation phase. The grain FPC project sought to enhance collaboration and alignment among stakeholders, ensure seamless integration of interventions across the crop value chain, bridge capacity gaps within the project team, and improve documentation and data management practices. Over the past five years, these refinements enabled the FPC project to focus on promoting sustainable agricultural development and contributing to the overall transformation of Ethiopia's agricultural sector. Hence, the objective of this paper is to document the progress, achievements, lessons learned, challenges, and issues encountered during the implementation of the project aimed at enhancing the commercialization of smallholder agriculture.

2. Materials and Methods

2.1. Description of implementation sites

The grain FPC project was a component of the Agricultural Commercialization Clusters (ACC) program, which was launched in November 2019. The project was launched to be implemented in 300 selected woredas, grouped into 31 geographic commodity clusters across seven regions with different priority commodities: Amhara (maize, wheat, tef, malt barley, sesame, and soybean), Oromia (maize, wheat, tef, malt barley, sesame, and soybean), Central Ethiopia (wheat, maize and tef) , South Ethiopia (maize, sesame, and soybean) , Sidama (maize) , South-West Ethiopia (maize, sesame, and soybean) and Tigray (wheat, tef, and sesame).

2.2. Operational Design/Model of the project

2.2.1. FPC establishment criteria

Clustering is an approach that groups farmers with adjacent farm plots to consolidate their farming activities and provide targeted support across key segments of the value chain, specifically in input and service supply, on-farm production, post-harvest handling and marketing. Farmers were selected and clustered based on various criteria for FPC cluster formation, to ensure effective project implementation across regions (ATA, 2019). Each farmer voluntarily joined a cluster, and contributed a minimum of 0.25 ha, ensuring the cluster has at least 15 ha of contiguous land. All farmers within a cluster agreed and be committed to cultivate the same crops and/or varieties and used full agronomic packages as uniformly as possible. Coordination and governance of these cluster activities were managed by the cluster management team. The grain FPC project targets 2.5 million smallholder farmers organized under 62,500 clusters who will plant the selected priority commodities on an estimated area of 2.5 million hectares (ATA, 2019).

The primary focus was to implement a farmer clustering approach that considers the proximity of farmland and farmers shared interests. These clusters have played a vital role in facilitating the production, access to inputs, and marketing of the agricultural commodities. The cluster establishment process involves bringing farmers together, fostering social cohesion, and encouraging collaboration. Farmers within the clusters can exchange ideas, share best practices, and collectively address challenges. Furthermore, the formalization of clusters through registration and incorporation provides a framework for governance, decision-making, and collective action. During the early stages of the FPC project piloting, significant efforts were also made to establish and formalize the clusters. This involved a process of socialization, registration, and incorporation. Training sessions were held for farmers, Development agents, experts, and cluster leaders on FPC concepts, cluster management, and the implementation of full packages.

2.2.2. FPC transition criteria

The idea of FPC transition was to transit from early stages towards professionalized and a coordinated Farmer Production Company. To transit to the next stage each FPC should pass the minimum basic criteria set at different stages. The end goal of the FPC transition was to attain a professional based Production Company. There were eight main transition criteria with minimum requirement to transit from one stage to the other stages. The eight main transition criteria were (1) adoption of full package recommendation, (2) a minimum land size under clustering per FPC, (3) adoption of larger- scale mechanization service in the cluster, (4) adoption of improved storage technologies and value addition practices in the FPC (5) degree of commercialization, amount sold as marketable surplus and sold through pre-signed agreement, (6) cluster management, (7) degree of coordination, and (8) farmers commitment to work as a cluster and sustainability of adoption of full package recommendations. Based on the transition criteria, the FPCs should transit from pre-basic, basic, intermediate and advanced to Production Company Level (Figure 1).

Source : ATA FPC Project document 2019

Figure 1. Transition stages of FPC from pre-basic stage to production Company stage

2.3. Data Collections and Analysis

Data were collected from the seven grain FPC project implementing regions, with support from development agents, woreda, and zonal experts in collecting data at kebele level. These data focused on various aspects, including cluster established, input utilization, area coverage, production volume of targeted commodities, surplus production, and the value of marketable surplus sold. The registration and validation of the number of FPCs were primarily conducted by the kebele's development agents (DAs) and followed by verification by the Woreda Office of Agriculture before being submitted to the Zone Department of Agriculture. Ultimately, commodity cluster coordinators compiled and submitted to ATI's Regional Agricultural Transformation Centres (RATCs).

The estimation of marketable surplus production was based on baseline data from the Ethiopian Statistical Services (EES), which helped in determining the percentage of annual marketable surplus for each priority commodity within each commodity cluster zone. Additionally, data regarding the surplus production sold for each commodity were collected from regional trade and market development offices, cooperative promotion agencies, and commodity-based Value Chain Alliance (VCA) platforms. This comprehensive approach ensured an accurate assessment of marketable surplus production and its associated sales. The collected data were cleaned and analysed using Excel software for descriptive statistics, and the results were summarized in tables, charts, figures, and graphs.

3. Results and Discussion

3.1. Cluster establishment, farmers registration and area coverage

The progress of the project indicated that about 2.46 million (98.4% of the initial target) farmers have been registered across more than 99,000 clusters (158.4% of the initial target) engaging in priority grain crop production cluster activities on 1.99 million hectares (79.6%

of the initial target) land (Figure 3). The area of land that was harvested, which amounted to 1.98 million hectares, was almost equivalent to the area that was initially planted (Figure 3).

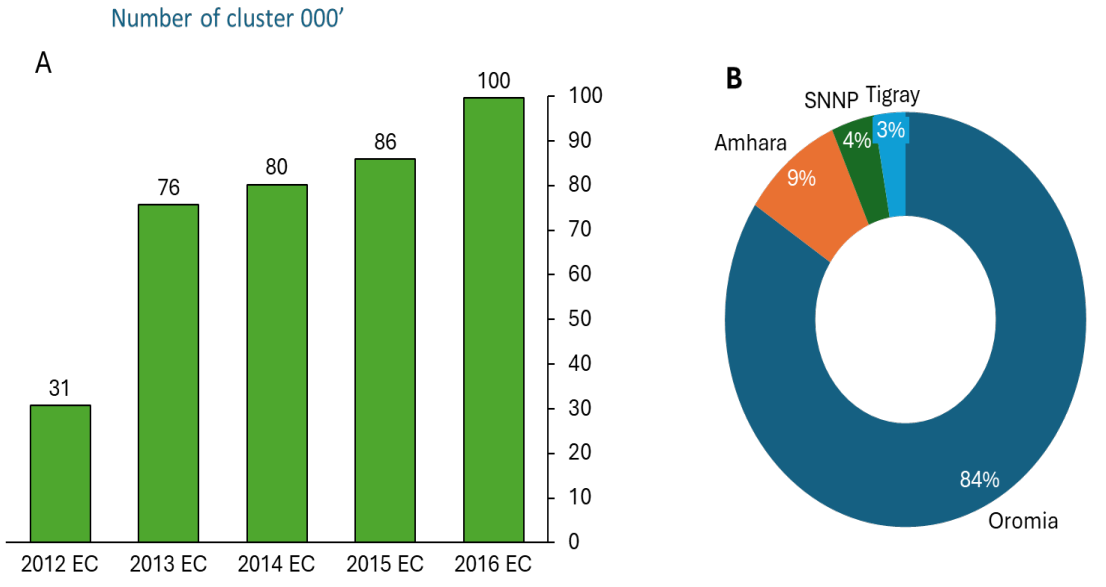

Figure 2: Clusters established (A) and share of cluster by regions (B)

The largest number of grains FPC clusters was established in Oromia Region (83, 981) followed by Amhara Region (8,989), accounting for 93.3% of the total achievement. Approximately 84% of the clusters established were in the Oromia region (Figure 2). In Oromia, wheat cluster was the largest cluster followed by maize cluster, whereas maize cluster was the largest in Amhara region (Figure 4).

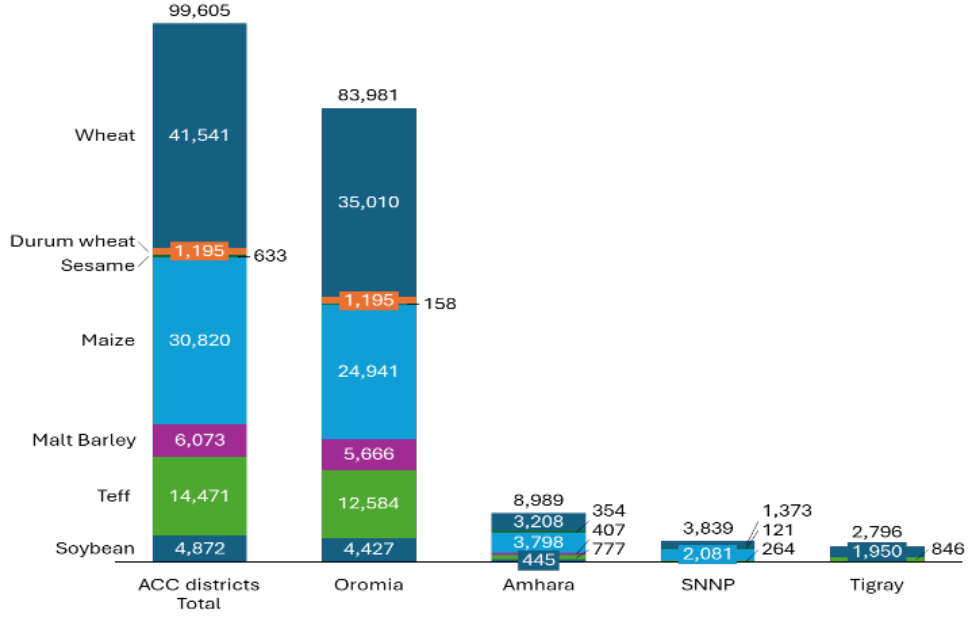

Figure 3. Number of Cluster established by commodities and Implementing regions

The overall achievement of the project indicated that the average number of farmers per cluster was 25, while the average land area per cluster was 20 hectares (Figure 4). This result indicates that the land area covered by each cluster exceeds the predetermined 15-hectare minimum area coverage set for the clusters (Figure 4). Notably, the region with the highest area coverage per cluster was Amhara, where clusters covered an average of 50 hectares. Additionally, Amhara recorded the highest number of farmers per cluster, averaging 96 farmers. On the other hand, the region with the highest average landholding per farmer was Oromia, with an average of 1.12 hectares per farmer (Figure 4).

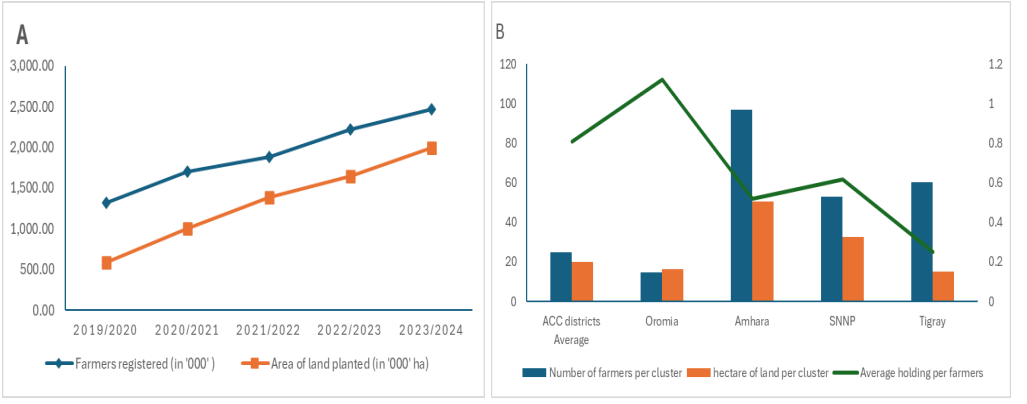

Figure 4. Trends of number of farmers, area planted (A), and land holding per farmer, average hectare and farmers per cluster(B).

The land clustering strategy has significantly eased the dissemination of agricultural technologies, extension services, mechanization, and access to collective inputs and aggregated outputs. This approach has not only expedited the ACC objectives for market-oriented production but has also boosted overall production and productivity levels. The Ministry of Agriculture has fully embraced and endorsed this approach, with more than half of the country's hectarage now covered by clusters this year. The satisfaction levels of FPC members regarding cluster membership were measured over three years (Figure 5). The results indicate that more than 75% of members are satisfied, and 97% have chosen to remain in the cluster. Additionally, 97% of farmers expressed a likelihood to recommend the FPC to other farmers.

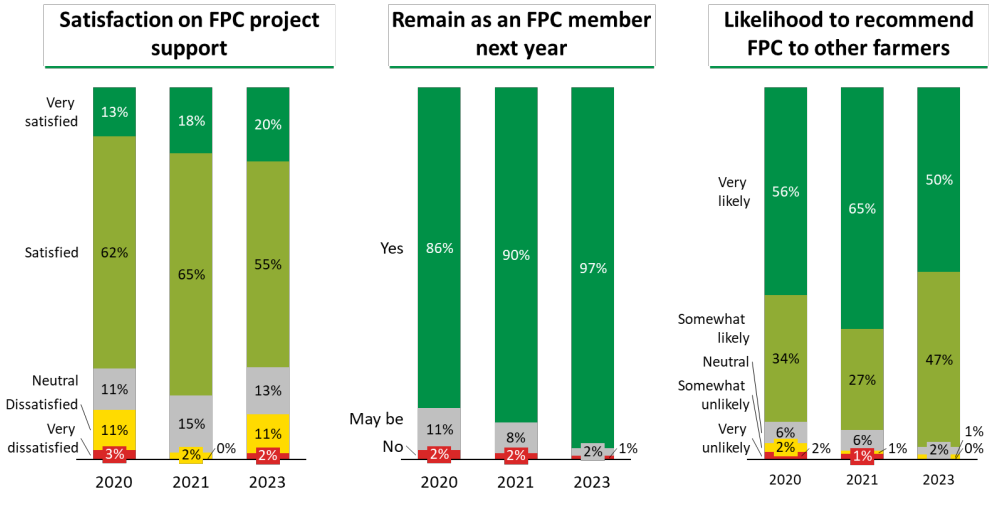

Figure 5. Farmers FPC member satisfaction level

3.2. FPC Transition

Despite the considerable success achieved in establishing clusters, the transition from one stage to another within the clusters remains relatively low. According to the 2021 transition assessment report, 75% of the total FPCs samples (13,341) were still in the basic stage, and only 4.5% reached intermediate stage (Figure 6). Similarly, the assessment carried out in 2023 showed 72.1% of total FPCs samples (685) were at pre-basic and basic stage whereas 27.6% of the total samples were in the intermediate stage, and only about 0.3% have reached the advanced stage (Figure 6). In 2024, the transition assessment that was conducted on 330 FPCs samples in Sidama, Central Ethiopia, South Ethiopia, and Southwest Ethiopia regions indicated that 16% and 23% were at basic and intermediate stages respectively whereas only one wheat FPC was at advanced stage.

Even though there has been slight progress in transiting FPCs from one stage to the next, a lot of effort will be required to transit FPCs from the basic stage to more advanced stages. It requires concerted efforts in terms of capacity building, availability of inputs and technologies, uses of pre- and post-harvest technologies, access to financing, market development, and strengthening of value chain linkages. Although all farmers in the FPC should adopt 100% full package recommendation as per the transition criteria, availability of inputs were the key factors that set back the transition of FPCs from one stage to the other stages. For example, the result of the 2023 end year assessment revealed that the average percentage of farmers who accessed quality seeds, fertilizers, and agro-chemicals for the last three years (2020-2023) were 88%, 93%, and 73% respectively. These three inputs are the main components of full package recommendation that affected to fulfil the minimum transition criteria to transit from one stage to the next stage. As per the transition criteria, however, at least 95% of FPC members should adopt improved seeds and fertilizer recommendations to transit from intermediate stage to advanced stage. Addressing the challenges and barriers related to transition, strategizing how to enhance access to inputs to farmers to adopt recommended input uses and revise/design new transition criteria based on the existing scenario is essential to enhance the speed up of the transition of FPC towards Farmer production Company.

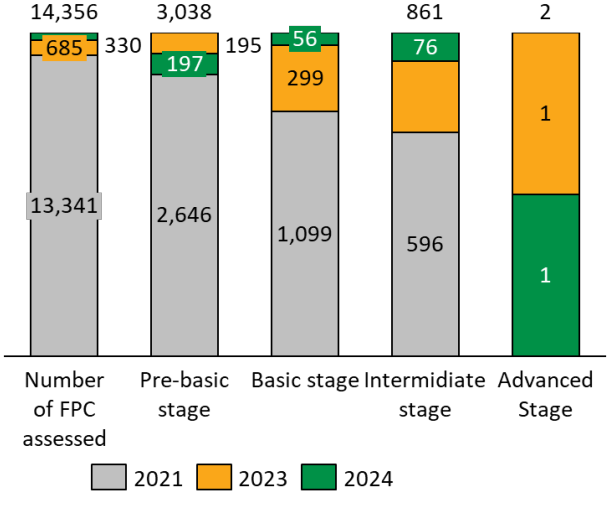

Figure 6. FPCs transition assessment conducted in all implementation regions

3.3. Model FPC

The main purpose of selecting model FPC was to accelerate transition towards professional based Farmer Producer Company through supporting in areas of key interventions that gear towards institutionalization. Having a model and reference FPC for each woreda is crucial for providing tailored support to professional business entities and ensuring institutionalization. This can serve as an example for other FPCs, helping them transition effectively between stages.

In this regard, the model FPC selection criteria were prepared to harmonize the selection procedure across all implementation regions. Some of the key criteria for selecting model FPCs were the progress or status of FPCs in terms of adopting inputs and technologies, trends of marketable surplus, trends of membership and increment of land size, governance and institutionalization, and other key indicators towards sustainability and commercialization of the FPCs. Based on the selection criteria, the assessment was conducted in 2024 in Oromia, Sidama and Central Ethiopia. Accordingly, 85 FPCs in Oromia region, and 4 FPCs in Sidama and 7 FPCs in Central Ethiopia region were selected as Model FPCs. However, the selection of model FPCs has not yet been done in Amhara and Tigray regions. In 2023/2024, special support were started for the selected model FPCs, particularly providing training for model FPCs' coordinators on business plan development and governance, supporting construction of warehouses, procurement of tractors and small-scale threshers, etc. This approach could be a good indicator to focus on few numbers of model FPC to transform to the intended Farmer Production Company.

3.4. Increased Adoption of Full Package

The crop package revision at the national level was conducted in 2019 and 2024. Accordingly, 21 crop package manuals were developed in collaboration with the Ministry of Agriculture, Ethiopian Institute of Agricultural Research, and regional agricultural research institutes. Regional bureaus of agriculture customized the revised packages to suit their specific regional contexts. From the revised manuals, the contents were extracted and translated into Amharic, Afan Oromo and Tigrigna for the 8028 Farmer Hotline platform.

Identified gaps during project implementations led to the identification of various research thematic areas. Over 26 research activities were supported, focusing primarily on multi-location variety selection for malt barley and sesame, demonstrating improved varieties and agronomic practices for soybean, conducting Wheat Fusarium Head Blight surveys and integrated management, soil health management, demonstrating prototypes of mechanization tools, and showcasing soybean recipe preparations.

Figure 7. Field days conducted

Large-scale demonstrations of improved varieties and recommended agronomic practices were conducted annually, tailored to regional contexts and identified gaps (Figure 7). For example, all the required agro chemicals and other inputs delivered to 8778 full package demonstrations across seven regions in the year 2019. Large-scale full package demonstrations were also carried out on FPC farmers on more than 9,800 ha in the last two years (2023–2024) of the project periods. A total of 750.6 tons of quality seeds (valued ETB 53.3 million) and 10,000 sackets of biofertilizers were also procured and distributed for model FPCs in 2022/2023. During the 2024 cropping season, large-scale demonstrations were also carried out on 100 hectares of land. More than 42 field days were organized across all regions in the year 2023 and 2024 to showcase the best practices (Figure 7).

In addition to FPC socialization and full package training (Table 1), various training sessions were held on a range of topics. These included training for female development agents (162) and model FPC women cluster leaders (66) on leadership, decision-making, and gender mainstreaming in the year 2024. Additionally, Training of Trainers (TOT) sessions were conducted in the same year for 139 female health extension workers and female development agents to enhance nutrition diversification within FPCs.

Table 1. Number of training/workshop events and participants

Types of events and participants	2019	2020	2021	2022	2023	2024
Farmers trained	3,330,000	2,060,000	2,176,279	1,948,391	2,310,242	2,555,922
DAs Trained	14,426	15,209	10,493	12,285	14,052	17,415
SMS trained	3,979	1,599	1,139	2,310	1,241	1,467
Regional leaders trained	1,061	–	–	–	–	–
VCA conducted	50	50	43	26	34	38
VCA attendees	1,049	3,134	2,846	1,705	826	2,044
Field days conducted	15	20	15	17	27	–
Field day participants	9,362	8,475	4,129	6,377	3,157	–

Sources: *ATA/ATI Annual and PMO Reports 2019- 2024*

3.5. Increased Access to Inputs

Being a member of a farmer production cluster offers invaluable access to essential agricultural inputs like credit, improved seeds, fertilizers and mechanization services. The primary focus has been on strengthening input availability for FPCs and facilitating greater access for farmers. Consequently, significant improvements have been observed in input utilization, along with notable increases in seed and fertilizer distribution, as well as the number of farmers benefiting from these crucial agricultural resources.

As a result of continuous awareness creation and socialization, large scale demonstration of full package recommendation, enhanced access to extension and inputs, number of farmers who accessed seeds and fertilizer as well as the amounts of inputs distributed have significantly been increased year after year. This enhancement has resulted in a notable 12% and 24% annual increments in volume of fertilizer access and seeds, respectively (Figure 8). Moreover, on an annual basis, there has been a remarkable 33% and 51% increase in number of farmers who accessed in fertilizer and quality seeds, respectively. (Figure 8).

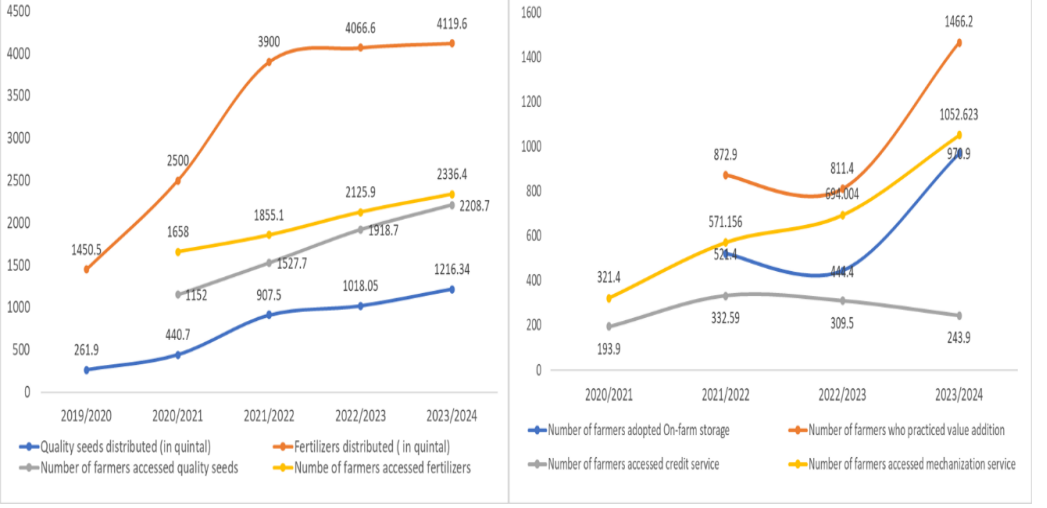

Figure 8. Number of Farmers who got access into inputs, and volume of inputs distributed (in '000').

3.6. Enhancing access and utilization of mechanization and credit

One significant improvement brought about by the FPC project was the increased utilization of mechanization services both before and after planting. At the end of the project period, over 44% (more than 1 million) of FPC farmers have accessed both pre and post-harvest mechanization services for their farming operations (Figure 8). The success in access to the mechanization service by the FPCs farmers was attributed to land consolidation efforts, demonstration of different pre and post-harvest mechanization technologies to model FPCs, enhanced linkage between service providers and the producers to continue support and facilitation of business-to-business linkages including value chain alliance meetings, continues support of the meccanization service centres, etc. For example, 54 tractors were provided for model FPC's farmers during the project periods (Figure 9). Other mechanization technologies, such as 120 seed drillers, 161 threshers/multi-crop threshers, 18 seed cleaner machines, etc. were demonstrated and promoted to smallholder farmers involved in FPCs (Figure 9). In addition, a total of 137,015 farmers obtained mechanization services from nine Mechanization Service Centres (MSC) supported by the ATI. Such intervention has brought a substantial progress of smallholder farmers who accessed both pre- and post-harvest mechanization services.

On the other hand, access to credit services among FPC members has not been fully realized as targeted. Only 10% of FPCs have so far managed to secure access to credit. In general, about 270,000 smallholder farmers have averagely accessed credit service in each year of the last four-years project period (Figure 8). The low performance was primarily due to various factors. The main challenges include limited access for smallholder farmers due to collateral issues, and minimal engagement from financial institutions. Addressing these obstacles is crucial for ensuring that FPC members can fully leverage credit facilities to enhance their agricultural practices and overall livelihoods.

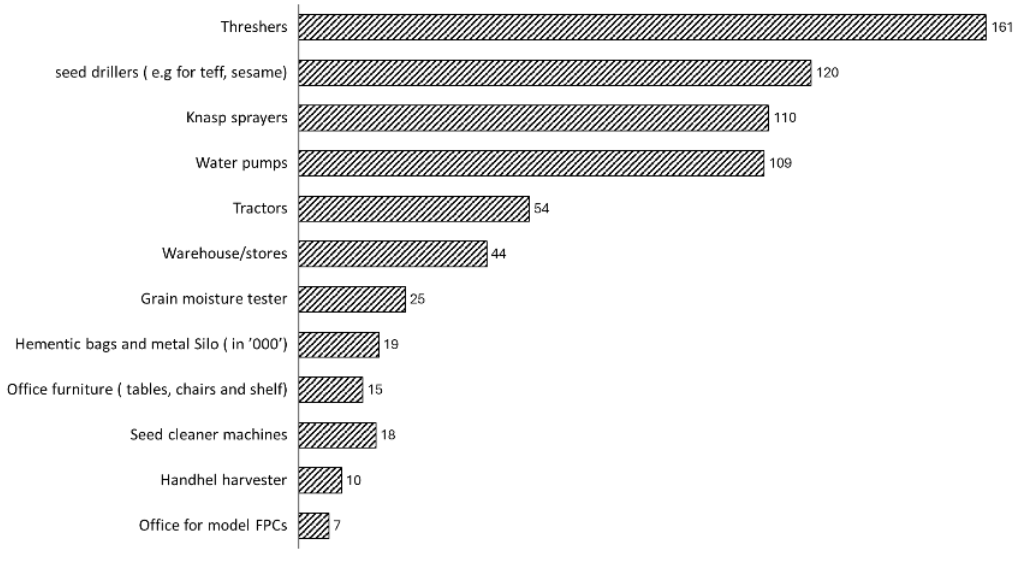

Figure 9. Different capacity enhancement agricultural machineries, implements, infrastructure supplied to model FPCs.

3.7. Productivity enhancement

The progress of yield increments of grain FPC's at farmers level were compared with Ethiopian Statistics Services (ESS's) (2021/2022) estimated national yield data and overall ACC program target set. The average yield per hectare of the five grain commodities increased by 91% and 31% compared to the baseline (1.71-ton ha^{-1}) and ESS (2021/2022) data, respectively. Except for soybean, which was lately included as one of the ACC commodities, remarkable percentage increments from 43% (Sesame) to 121% (maize) over the baseline were recorded for each commodity (Figure 10). Overall, except for sesame and soybean, the average year-to-date productivity were achieved by 81% to 162% in comparison to the target set for the ACC program (Figure 10), which is remarkable achievement. Key factors contributing to these increments in productivity were due to the remarkable achievements of key interventions such as clustering techniques, comprehensive package implementations, optimized input utilization, and effective crop management practices. However, it is still possible to increase the yield of sesame and soybean and other cereal crops in general through enhancing availability and supplies of inputs, adoption of improved technologies, etc.

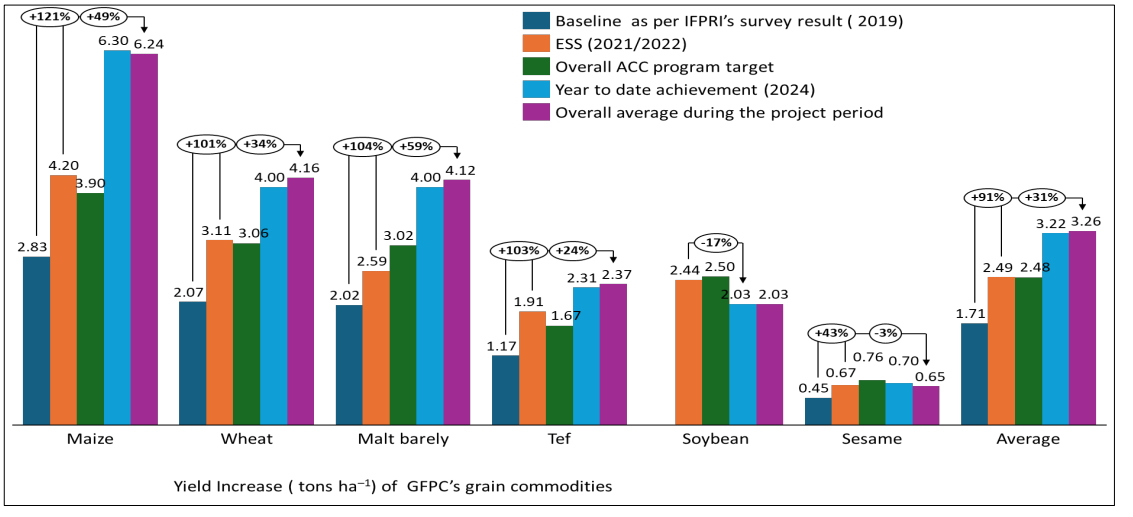

Figure 10. The year-to-date and overall average productivity of the six grains

3.8. Enhancing Access to on-farm storage and practicing value addition

Awareness campaigns and demonstration of different technologies tailored for farmers within the FPC clusters have significantly boosted the adoption of post-harvest handling techniques for grain crops and the integration of primary value-addition processes, such as cleaning, sorting, grading, etc. In each year of the 2022,2023,2024, an average of 646,000 and 1.1 million smallholder farmers have used on-farm storages and value addition practices respectively. These on-farm storage practices were predominantly hermetic bags (e.g. PICS), metal and plastic silos, and warehouses (Figure 9). For example, 19,000 hermetic bags and 72 metal silos were demonstrated to the smallholder farmers participate in FPCs, and 44 warehouses were being constructed for model FPCs (Figure 9).

Following the harvest season, farmers actively engage in value-adding activities like sorting and grading their grain crops to ensure optimal storage conditions and enhance marketability.

This trend reflects a positive trajectory, with more than half of the farmers enrolled in the cluster now actively involved in primary processing activities. This not only signifies a growth in the adoption of best practices but also underscores a proactive approach towards maximizing the value derived from agricultural produce within the community.

3.9. Direct Support for Model FPCs

In addition to facilitating access to improved seeds and fertilizers for FPC farmers, various direct supports were provided to enhance agricultural practices. Direct seed purchases and distributions were carried out for targeted interventions, particularly in conflict-affected regions. Large-scale demonstrations were conducted to showcase improved agricultural packages on model farmers' plots, serving as learning platform for other farmers. To facilitate the transition of FPCs from one stage to another and eventually to a company level mainly in focusing the model FPCs, different machineries were purchased and distributed to support model FPCs. This included over 40 tractors, various 161 multi-crop shellers, 109 irrigation water pumps, and other equipment (Figure 11).

Figure 11. Sample tractors purchased and distributed

To ensure the effective operation of the acquired machinery, training sessions were conducted for user farmers on handling, operating, and maintaining the equipment. Furthermore, offices were constructed and equipped with necessary office furniture and equipment to assist model FPCs in establishing their own operational spaces (Figure 12). These interventions aimed to strengthen the capacity and infrastructure of model FPCs.

Figure 12. Model FPC offices

Thirty-Five Seed stores and eight warehouses were constructed for model FPCs. Alongside these constructions, seed cleaning machines were procured and installed for seed producer FPCs. Furthermore, cost-effective and environmentally friendly storage materials like PICS bags and metal silos were acquired and distributed to farmers (Figure 13).

Figure 13. Seed store constructed and finalized at Munesa and Botor Tolay and Bale Gesger, Sinana and Dodola site

3.10. Creating and Strengthening market linkage

Farmers within FPCs consistently boosted their production output annually through a multitude of factors. The expansion in both the number of participating farmers and cultivated land area under the clustering approach over the years has directly led to a notable increase in the overall production volume. Furthermore, the adoption and effective use of improved agricultural inputs play a significant role in enhancing the production and productivity of grain crops.

At the end of the project period, the total volume of six grain crops (wheat, maize, teff, sesame, malt barley and soybean) productions was 8.32 million tons from 1.923 million ha of land. On other words, the production volume, which stood at 2.54 million tons at the beginning of the project, has now increased to an impressive 80.32 million tons (Figure 14A). A total of 182,893 tons of soybean grain crop was harvested from 90,102 ha of land in the year 2023/2024. Maize (4.06 million tons) followed by wheat (2.99 million tons) and teff (697,151 tons) were the largest volume of production recorded at the end of the project period. In general, about 69% of the total volume of production in ACC woredas were achieved by grain farmer production cluster project. This remarkable growth can be attributed to various interventions aimed at augmenting marketable surplus and facilitating pre-marketing contract agreements.

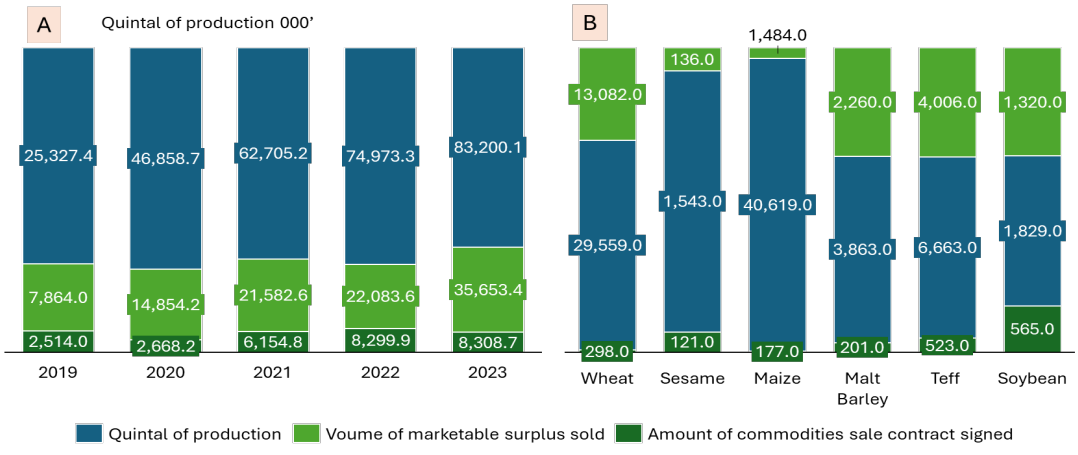

Figure 14. Year-to date volume of production, and surplus production sold (in qt)

In 2024, the total surplus production sold was 3.57 million tons with the value of ETB 174.31 billion, but the average annual surplus production sold was 2.01 million tons. The average percentage of surplus production sold of each grain crop was 37% for maize, 44% for wheat, 59% for malt barley, 59% for teff, 72% for soybean and 88% for sesame. Overall, the average percentage of surplus production sold was 60%. The surplus production sold through contract signed agreement also showed encouraging results. The year-to date total surplus production sold as per contract signed agreements was high for sesame and malt barley (89%) while 12% for maize and teff, 23% for wheat and 43% for soybean. Overall, 798,320 tons of the grain produce were sold with the value of ETB 39.5 billion through contract signing agreements. This increment shows a shift towards a more market-oriented approach of production. The improved aggregation capacity, enhanced bargaining power for farmers during output sales, and inflation have collectively contributed to the increase in the value of

marketable grain and contract marketing. These figures underscore the significant strides made in optimizing marketable surplus and contract marketing values, reflecting a more efficient and lucrative market engagement for farmers within the agricultural ecosystem.

Furthermore, beyond training workshops, activities such as Value Chain Alliance (VCA) meetings were held quarterly, focusing on season-based activities corresponding to specific crop commodities. These meetings gathered participants from various sectors including the Ministry of Agriculture (MoA), Regional Bureaus of Agriculture (RBoA), research institutes, research centres, universities, development partners, associations, and processors. The agenda of these seasonal meetings involved sharing responsibilities and insights, fostering collaboration among stakeholders for effective implementation of project intervention.

4. Conclusion and Recommendations

The implementation of Farmers' Production Clusters (FPCs), aimed at enhancing the production and productivity of priority grain crops and increasing surplus output, has demonstrated encouraging results. The approach has improved farmers' access to inputs, promoted the adoption of full agronomic packages, and enabled the cultivation of crops in contiguous cluster areas. Over time, notable improvements have been observed in production volumes, productivity levels, and the proportion of surplus production marketed by farmers. These outcomes indicate that the FPC approach is an effective model for improving the productivity and income of smallholder farmers. As such, it should be further scaled up to non-ACC woredas and extended to additional commodities, while ensuring that the core principles of the FPC model are effectively implemented. Moreover, collaborative platforms such as Value Chain Alliances (VCAs) have proven instrumental in addressing shared challenges and strengthening accountability among stakeholders across the value chain.

Despite these positive outcomes, several challenges remain. One of the most critical issues is the lack of a formal policy framework that recognizes FPCs as legal entities. Addressing the legalization of FPCs should therefore be considered a high priority. In addition, the relatively low transition of FPCs to more advanced stages is associated with factors such as sub-optimal adoption of full agronomic packages, limited capacity among extension agents, inadequate access to input and output financing, and weak market linkage activities within clusters. Addressing these constraints requires strategic interventions supported by stronger public–private sector engagement to ensure sustainable value chain development.

To tackle the challenge of limited access to financial services among FPC members, it is recommended that dialogue platforms be established to bring together financial service providers and representatives of smallholder farmers. In parallel, strengthening access to conventional and community-based financial mechanisms, such as *Ekub*, *Edir*, and farmer-to-farmer lending, can provide alternative sources of financing for agricultural activities. Continuous dialogue with policymakers is also essential to improve the enabling environment for smallholder farmers.

Furthermore, limited access to mechanization services remains a constraint in the implementation of the FPC approach. Efforts should therefore focus on improving farmers' access to mechanization through strengthened linkages between service providers and FPC

members. Establishing and facilitating linkage forums can promote service arrangements such as renting tractors and combine harvesters to meet farmers' machinery needs. In addition, strengthening partnerships with mechanization service providers and commissioning newly established mechanization service centers will further enhance access to mechanization services and support improved agricultural productivity.

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The Role of Cooperative Based Seed Production in Transforming Intermediate seed Sector

Habtamu Diriba*, Weyessa Garedew, Dagnachew Lule, Zerihun Abebe, Yitbarek Semeane, Reta Wagary, Mersha Tesfa, Ashebir Deme, Daniel Lemlem,Gezahegn Walelign, Abrham Gebremichael, and Naol Gaddisa,

Agricultural Commercialization Cluster (ACC) Vertical, Ethiopian Agricultural Transformation Institute (ATI),
P.O. Box 708, Addis Ababa, Ethiopia
*Corresponding author: diribhabtamu@gmail.com

Abstract

Seed is the most critical input for enhancing agricultural productivity and driving economic growth. However, limited access to demand-driven, quality seed remains a long-standing challenge in Ethiopia. The formal seed system primarily focuses on a few crops, such as maize and wheat, leaving a significant demand unmet and neglecting other crops that are vital for food and nutritional security. The Cooperative-Based Seed Production Project was designed to bridge the gap between the formal and informal seed system, addressing deficiencies in the supply of low-profitability crops. The objective of this paper provides evidence on the role of cooperative-based seed production in transforming the intermediate seed system and achieving strategic objectives, using a mixed-method approach that combines quantitative and qualitative analyses. The results show that 14 unions successfully transitioned from out-growers to licensed seed producers by strengthening their physical, technical, and institutional capacities. The project supported 19 unions, encompassing 276 primary cooperatives with 18,191 farmer members (including 3,171 women) and contributed 123,000 quintals of seed to the national supply. The project was found to be highly relevant, as seed remains the government priority, and the limited supply of quality seed continues to pose challenges. Its sustainability is evident, given that unions and local private producers have remained resilient and continue producing even under stress conditions.

Keywords: Crop, input, food security, private producers, unions

1. Introduction

Increasing agricultural productivity is crucial for Ethiopia, where agriculture remains the backbone of the national economy. The sector employs a large share of the workforce, plays a central role in ensuring food security, generates income for millions of smallholder farmers, and contributes to economic development by enhancing export potential. Agricultural productivity improvements depend largely on the availability and effective use of key inputs such as fertilizers, agrochemicals, improved seeds, and extension services (Araya & Sung-Kyu, 2019). Among these inputs, seed is considered one of the most indispensable elements in crop production (MoA & ATA, 2017). The pace of progress in crop production therefore depends significantly on the extent to which high-quality seeds and planting materials are generated, multiplied, and made readily accessible to farmers.

However, limited access to quality-assured seed remains a major constraint in Ethiopia. As a result, many farmers continue to plant grain instead of certified seed, which can lead to yield reductions of at least 30% (Mezgebo, 2019). In contrast, the use of quality seed from improved varieties can increase yields by up to 50% per hectare (CGIAR, 2015). Despite this potential, many farmers still face difficulties in accessing improved seeds through formal supply systems, as numerous released varieties are not sufficiently popularized, produced in adequate quantities, or delivered to farmers on time and at affordable prices (Integrated Seed System Development, 2014).

The Ethiopian seed sector has traditionally been dominated by a limited range of crops. Both public and private seed producers primarily focus on a few cereal crops, particularly hybrid maize and bread wheat (Shimelis, 2015), while paying limited attention to less profitable crops such as self-pollinating cereals, pulses, oil crops, and root crops that are critical for the food security of smallholder farmers. Consequently, in previous decades, about 80% of seed distribution and 85% of cultivated land relied on locally sourced seed due to the limited supply of quality seed in the country (Dejen, 2021).

Recognizing these challenges, Ethiopia's Seed System Development Strategy (MoA & ATA, 2017) identifies three interrelated seed systems: formal, intermediate, and informal. Strengthening decentralized seed production and distribution mechanisms that bridge the formal and informal sectors is essential, particularly to address the supply gaps for less commercial crops that are not adequately served by public and private seed companies. Cooperative-Based Seed Production (CBSP) presents a significant opportunity to meet part of this demand at the national level. Nevertheless, the effectiveness of CBSP initiatives has been constrained by a range of internal and external bottlenecks, including systemic limitations, institutional weaknesses, and capacity gaps.

At the same time, private sector participation in seed production remains limited. Local private seed producers are generally small-scale and not yet well developed as competitive seed businesses. Their contribution to the country's total seed production remains relatively low, accounting for only about 8% (ATA, 2021). Expanding private sector engagement, particularly in crops beyond maize, is therefore essential for ensuring a sustainable supply of improved seed in Ethiopia.

In response to these challenges, the Cooperative-Based Seed Production (CBSP) project was initiated by the Ethiopian Agricultural Transformation Institute (ATI) in August 2014 and implemented across six regions: Amhara, Oromia, Sidama, Central Ethiopia, South Ethiopia, and Tigray. The project aims to reduce the significant mismatch between seed demand and supply by strengthening the capacity and operational models of CBSP unions and local private seed producers. Through these interventions, the project seeks to address the needs of neglected crops and better meet the demands of farmers across diverse agro-ecological zones.

The overarching goal of the project is to contribute to the transformation of the intermediate seed sector by significantly increasing the quality and volume of improved seed produced and marketed, ultimately leading to higher crop yields and improved incomes for farmers.

Accordingly, this study aims to assess the role of the CBSP project in transforming the intermediate seed sector and its contribution to achieving Ethiopia's seed system development objectives. Specifically, the study evaluates the performance of CBSP unions and local private seed producers across the six regions where the project has been implemented: Amhara, Oromia, Sidama, Central Ethiopia, South Ethiopia, and Tigray.

2. Materials and Methods

2.1. Study area:

The study focused on assessing the performance of CBSP unions and local private seed producers, across six regions: Amhara, Oromia, Sidama, Central Ethiopia, South Ethiopia, and Tigray.

2.2. Research design:

The research design involved organizing, collecting, and analyzing existing data for valid research conclusions. The study primarily relied on synthesizing information from secondary sources, including organizational reports and records, peer-reviewed journal articles, and relevant online resources.

2.3. Research data:

Both quantitative and qualitative data were used to analyze the result and draw conclusions. Hence, the assessment was used secondary research approach for a systematic investigation which depends on existing data such as annual reports, new letters, and the CBSP project data sheet. The qualitative and quantitative data collected from secondary sources were systematically analyzed by grouping, mapping, and summarizing using graphs, and charts. Finally, the findings of the study were interpreted through description.

3. Results and Discussion

3.1. Improved seed demand and supply

The result showed there has been a high demand for improved and quality seeds compared with the actual supply in the past five years (figure 1). This trend indicates that there is long term significant gap between improved seed demand and supply. The demand is significantly increasing (40%) while the pace of the increase in seed production and supply shows fluctuation and is not responding (14%) to rapid increases in demand.

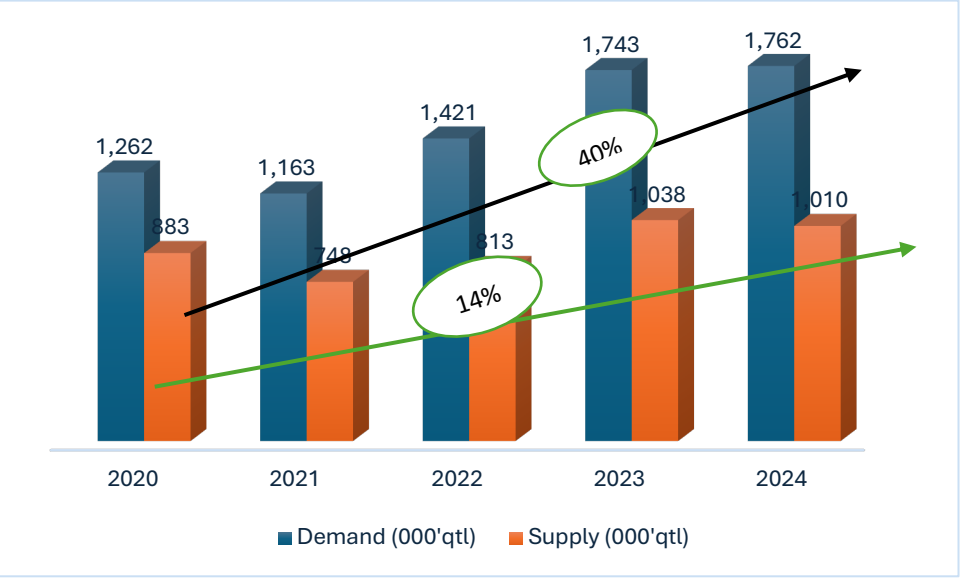

Figure 1: Seed demand and supply trends (Source: MoA 2024 report)

3.2. Seed production performance of CBSP unions

The result of the report shows that the seed production trend of CBSP unions and private producers for five years (2020-2024) has fluctuated (figure 2). These fluctuated trends in seed production resulted from inconsistent EGS supply, security problems in Oromia, Amhara, and Tigray regions to conduct field inspection for quality control and difficulty to aggregate produced seeds, and limited access to finance for seed aggregation. On the other hand, since local farmers engaged in seed production and marketing, the cooperative based seed production model is more resilient and consistently producing and supplying improved seed to local community in situations in which formal seed systems are unable to produce and market. This result indicates that CBSP unions and local private seed producers are playing a considerable role in producing and supplying quality seeds for farmers and are more adaptable and sustainable in stress conditions.

Figure 2: Seed Production trends of CBSPs 2020-2024 (Source: CBSP unions and private production report)

Figure 3: Gudeta Gonfa Seed farm

Figure 4: Guna union's Seed in storge

3.3. Contribution of CBSP unions and private producers

The public seed enterprises were a dominant seed supplier with the share of 63%, private seed producers share 20%, while unions cover 17% of seed supply in the six regions (Oromia, Amhara, Sidama, Central Ethiopia, South Ethiopia, and Tigray) of Ethiopia (figure 5). The baseline assessment conducted by the ATI at the beginning of the project indicated that the contribution of unions to national seed supply was 5%. However, currently the result of this assessment revealed that the average contribution of CBSP unions increased to 17% of national seed supply.

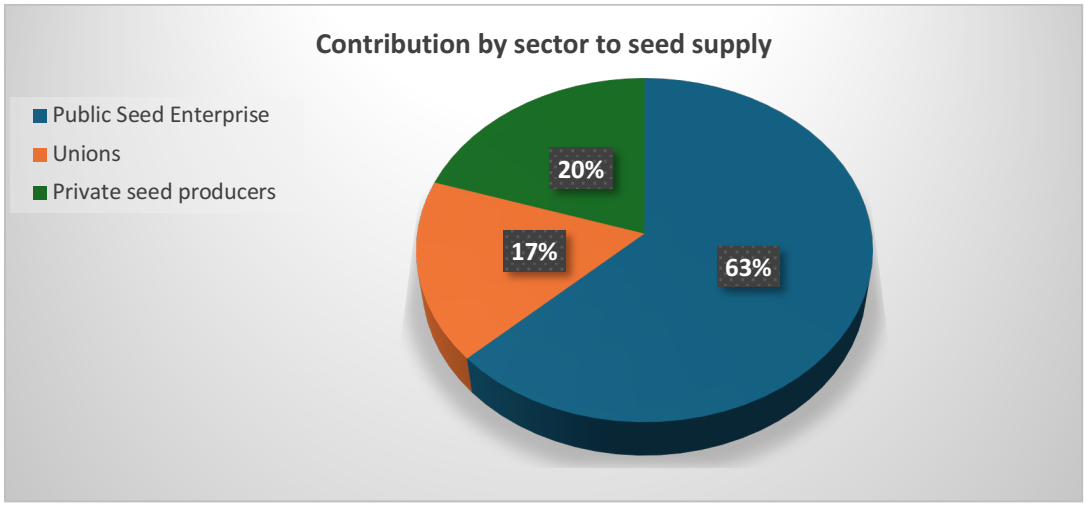

Figure 5: Contribution of different seed systems to national seed supply (source: ATI Annual Report)

3.4. Performance of CBSP unions

3.4.1. Institutional performance

The project supported the establishment of 13 CBSP unions: Oromia (5), Amhara (3), Central Ethiopia (2), South Ethiopia (1), and Tigray (2) unions and strengthening of one existing

union in Central Ethiopia. According to the CBSP project reports, and final evaluation result, 14 (13 new and 1 existing) unions successfully received technical and financial support, became registered, and licensed, as accredited seed producers.

With the intensive support provided by ATI, 14 CBSP unions with 196 affiliated primary cooperatives that involved 17,733 memebers (2,658 female) were successfully transformed and able to independently produce and market quality seed that could meet agricultural input regulatory requirements. In addition, as part of scaling up support, five additional CBSP unions and 15 local private seed producers supported of which three CBSP unions took physical and technical support while 12 only took technical are in progress.

3.4.2. Technical performance

The CBSP project terminal reports revealed that the soft skill capacity of unions internal staff, committee members of primary cooperative, seed producer farmers, local private seed producers, experts from government office are strengthened. This capacity building intervention was provided to 18,191 farmers (3,171 female) and 645 experts (80 female) from seed producers and government office. Furthermore, publishing and distributing of 4,000 training modules in local languages (Amharic, Afan Oromo, and Tigrigna) to 14 CBSP unions used for the sustainability of the technical capacity building initiatives. As a result, unions, primary cooperatives, local private seed producers, and farmers supported by the project have capacitated in quality seed production, business management, and organizational management.

3.4.3. Physical performance

To strengthen the physical capacity of CBSP unions and local private seed producers, 8 office buildings, 13 seed processing plants, 37 seed storage, of which 29 of them were already completed whereas 8 (5 for CBSP unions & 3 for private seed producers) are in progress. 20 mini-seed laboratories of which 12 are already completed whereas 8 (5 CBSP unions and 3 private seed producers) are still in progress. In the similar way, 3 diffused light stores, 1 potato lath house, 9 training centers, 7 tractors, 7 field vehicles, 5 truckers and 17 motor bikes were provided on cost sharing approach (70% ATI, 30% unions). For the physical capacity building ATI invested a total amount of Birr 227 million (figure 6) of which 62% of the investment is for construction of standard seed storage.

All the existing 14 CBSP unions supported by ATI were equipped with basic standard physical seed facilities requirement to successfully run all components of the seed business. The physical capacity building involves 19 CBSP unions and three local private seed producers in the six regions (Oromia, Amhara, Sidama, central Ethiopia, South Ethiopia, and Tigray) and contributed to enhance the production, processing, and marketing of quality seed that fulfil to meet the seed regulatory standard.

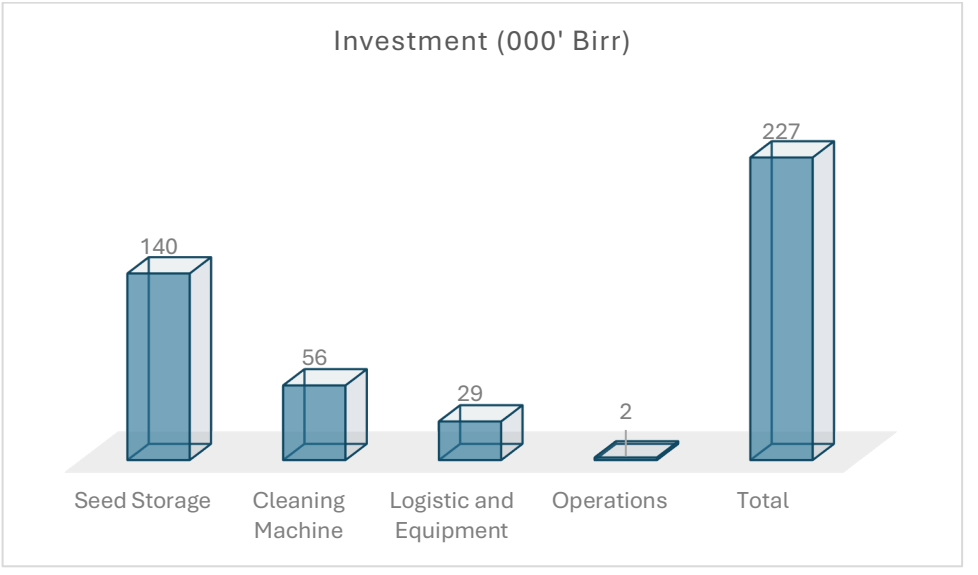

Figure 6: Investment in physical facilities of CBSP unions. (Source: ATI terminal report)

Note: Logistics and equipment include laboratory equipment, generators, track, tractor, field vehicle, and motorcycle

Office of Andinet Raya union (Tigray) | Seed cleaning facility of Erer union (Oromia) | Seed storage and Track Galema union (Oromia) | Tractor Ediget union (Central Ethiopia) | Mini-seed laboratory Andinet Raya union (Tigray)

Figure 7: CBSP unions' seed facilities

3.5. Seed recovery performance of CBSPs

The project progress reports reveal that the overall seed recovery rate of CBSPs unions and local private supported by ATI increased to 70% in 2024 compared to 23% before 2016 (Figure-8). The seed recovery rate performance varies across the region. The Tigray Agricultural Transformation Center (TATC), Amhara Agricultural Transformation Center (AATC), and South Agricultural Transformation Center (SATC) regions showed better performance as compared to the Oromia Agricultural Transformation Center (OATC). The better performance in Tigray and Amhara regions resulted from better commitment and support from the regional BoA and Cooperative Agency through facilitating access to finance for seed aggregation as Amhara BoA provided interest free short-term credit to the three (Guna, Tegulat, and Edget) unions in the region while the recovery rate in Oromia is relatively low due to limited access to finance for seed aggregation. The better performance for the

seed recovery rate in SATC resulted from that majority of the seeds produced by local private seed producers on their own land. This result indicates that the seed recovery rate performance is better in the region in which regional BoA and CPA committed to support and facilitate access to finance for seed aggregation and in the region in which local private producers engaged and produced on their own land.

On the other hand, unions managers explained that success on seed recovery rate relay on access to finance at affordable interest rate, seed pricing system, time of seed aggregation, and contract enforcement. Loans from commercial institutions are not encouraging due to high interest rates and are not affordable for the seed business. In most cases, seed price is arranged through the coordination of regional BoA which is claimed to dominate the public seed enterprise. Since public seed enterprises are receiving different types of support, land for seed production and relatively low cost the set price is not attractive for seed producer farmers. Normally, the seed aggregation time coincides with crop harvesting period in which the grain price is lower than any period. This situation results in low seed prices and demotivates seed producer farmers to provide their seed to respective primary cooperatives as per the contractual agreement. Poor contract enforcement is also identified as a challenge for seed aggregation and affecting the seed recovery rate of CBSP unions.

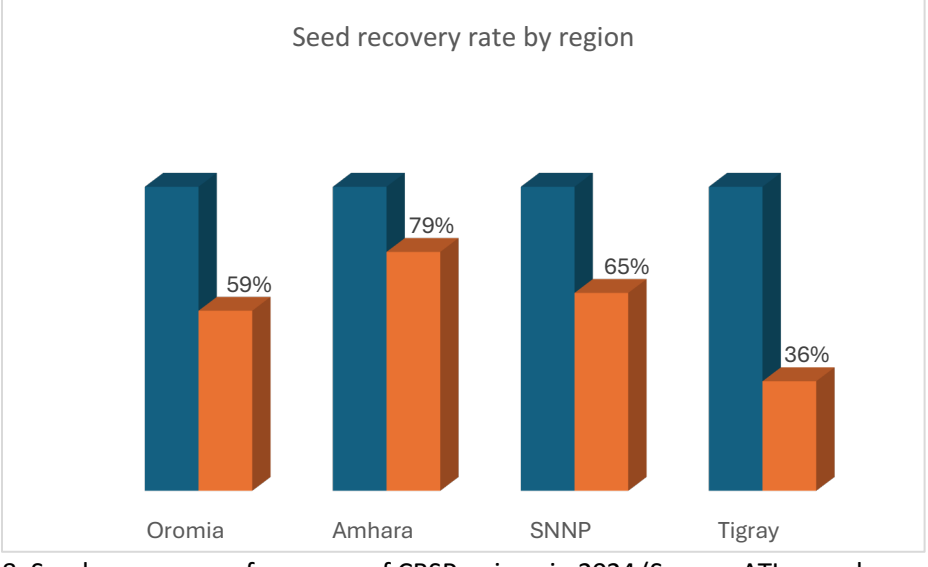

Figure 8: Seed recovery performance of CBSP unions in 2024 (Source: ATI annual report)

3.6. Trend of farmers engagement in seed business and farmers accessed to improved seed

As indicated on the result of the assessment in figure 9 and 10, the trends of farmers engaged in seed business and trends of farmers accessed improved seed fluctuate from year to year. The trend of farmers engagement in seed business fluctuates as the result of inconsistent EGS supply and security problems in the country, especially in Oromia, Amhara, and Tigray regions; while the inconsistency of number of farmers accessed to improved seed resulted from inconsistency of seed production and supply trend indicated in the above figure 2. Generally, sustainable demand driven EGS supply, security and access to finance for seed production and marketing have highly influenced the number of farmers

engagement in seed business as well as farmers' access to improved seed. This resulted in a decrease in production and productivity as well as income of farmers.

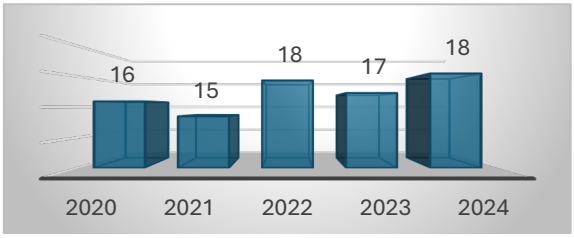

Figure -9: Trends of number of farmers engaged in seed business (000')

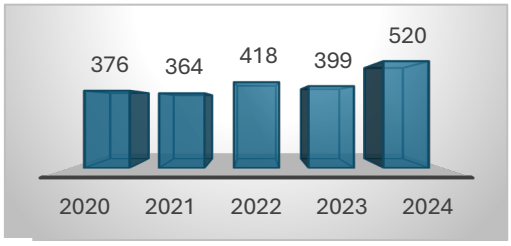

Figure-10: Number of farmers accessed to improved seed (000')

3.7. Linkage

To enhance the efficiency of product and service flows, as well as coordination among seed producers, strengthening linkage among actors in seed value chain is essential. In this regard, targeted support was provided to Community-Based Seed Producer (CBSP) unions and private seed producers through workshops, discussion forums, and farmer field days, aimed at fostering strong and sustainable partnerships.

As a result, supported seed producers have been successfully linked to key services, including access to Early Generation Seed (EGS), finance, and output markets. Notably, all 14 existing seed unions are now able to meet the collateral requirements of financial institutions and access loans from formal sources.However, challenges remain. Limited availability of EGS and recent changes in credit directives have constrained access to both EGS for seed production and finance for seed aggregation. In addition, the relatively high interest rates on bank loans make them less affordable for CBSP unions, given the narrow profit margins in the seed business.

4. Conclusion and Recommendations

Cooperative Based Seed Production (CBSP) model is one of the best strategies to decentralize production and promote marketing of improved seeds. It enhances availability and access to quality seed for farmers. Strengthening the institutional capacity of CBSP and private seed producers is one of the best strategies to decentralize improved seed production and marketing to narrow the huge gap between seed demand and supply. Inconsistent demand driven EGS supply, limited access to finance and security problems are among the challenges identified for sustainable increase of quality seed production and marketing.

Scaling decentralized seed production approach through supporting institutional capacity of CBSPs and local private seed producer is crucial. For sustainable EGS supply promoting market-based breeder and pre-basic seed production at agricultural research institutes, engaging potential seed producers in EGS production and facilitating strategic linkage in seed value chain are strategic options. To improve access to finance for improved seed production and marketing, supporting implementation of agricultural financing policy and promoting credit-based seed aggregation through incentive pricing should be used.

The assessment result revealed that the main challenges for successful demand driven seed production and marketing in Ethiopia includes focus of formal producers on few commercial crops and neglecting low profitable crops important for food and nutrition security. Limited access to finance, inconsistent demand driven EGS supply, and security problems are also among the key challenges for sustainable seed production and supply to fill seed demand and supply gap. Hence, solving these critical challenges important to advance CBSPs.

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Exploring the Scalability of Improved Maize Varieties in Ethiopia: Insights from the Integrated Innovation System and Scaling Scan Framework

Daniel Nigussie*[1], Getnet Alemu[2] & Million Gebreyes[3]

[1]Department of Rural Development and Agricultural Extension, College of Agriculture and Environmental Science, University of Gondar, Ethiopia. PO.Box 196
[2]Institutes of Development and Policy Research, Addis Ababa University, Ethiopia
[3]International Livestock Research Institute, Sustainable Livestock System (Social Scientist), Ethiopia
*Corresponding author email: any_266@yahoo.com

Abstract

This study examines the processes and challenges involved in scaling improved maize varieties in Ethiopia by comparing public agricultural research centers and private companies, specifically Pioneer Hi-Bred Seeds Ethiopia Plc. Using an Integrated Innovation System and the Scaling Scan Framework; it evaluates technological, institutional, and systemic factors influencing scalability. Findings indicate that while Pioneer's hybrid variety (P3812W or "Limu") demonstrates high farmer demand, public-private collaboration, and market potential, its scalability is hindered by weak local integration and limited public sector support. Conversely, public sector varieties benefit from institutional legitimacy and governance backing, yet suffer from weak business cases, value chain gaps, and poor leadership. The paper concludes that sustainable scaling requires a coordinated, multi-stakeholder platform to enhance knowledge sharing, financing, and institutional alignment. policy recommendations are offered to facilitate systemic transformation in Ethiopia's maize sector.

Keywords: Agricultural research, Pioneer's hybrid variety, Public-Private Partnership

1. Introduction

The scaling of agricultural innovations is a cornerstone of Ethiopia's agricultural development strategy, with particular emphasis on improving productivity through the dissemination of high-yielding crop varieties. Among these, maize a staple for millions has received substantial investment in both research and extension. Despite this, translating research outputs into impactful outcomes at scale remains an ongoing challenge. Adoption of improved maize varieties, while increasing, continues to lag expectations due to systemic and institutional bottlenecks.

Previous studies often viewed scaling as a linear process, focusing narrowly on the diffusion of individual technologies. However, contemporary thinking emphasizes that innovation scaling is a complex, non-linear process embedded within broader social, economic, and institutional systems. It demands a systems thinking approach that accounts for the interplay of actors, institutions, and infrastructures.

This paper seeks to bridge that gap by using both the Integrated Innovation System framework and the Scaling Scan methodology to assess how public and private institutions in Ethiopia scale maize innovations. Specifically, it compares the scaling experiences of public

research centers and Pioneer Hi-Bred Seeds Ethiopia Plc., using qualitative data from key informants and focus group discussions in Amhara Region.

By identifying key enablers, constraints, and systemic gaps, this study contributes to understanding what works in scaling agricultural innovations, and what must change to replicate successful interventions scale. The findings provide actionable insights for policy makers, development partners, and private actors striving to transform Ethiopia's maize sector.

2. Materials and Methods

2.1. Rethinking the Concept of Scaling

Scaling refers to the broad adoption and integration of innovations technological, institutional, or social across geographies and stakeholder groups. It encompasses not only the spread of technologies but also institutional change and system-level transformation. Traditional models of scaling, often rooted in linear diffusion theory. Hartmann & Linn, 2008; Linn and Hartmann, 2010, have proven inadequate in addressing the complexity of agricultural systems. These models typically focus on individual innovations and ignore the wider context in which innovations are embedded.

In contrast, contemporary approaches position scaling as a systemic process involving multiple actors, feedback loops, and institutional dynamics (Hall & Dijkman, 2019; Woltering *et al.,* 2024). Scaling is now increasingly viewed not as a goal, but to contribute to systems transformation and sustainable development goals (Wigboldus *et al.,* 2016; Sartas *et al.,* 2020). This perspective recognizes that scaling involves not only the dissemination of technologies but also changes in governance, finance, infrastructure, and social norms.

2.2. Innovation Systems Thinking

The Innovation Systems (IS) approach emphasizes that innovation is not an isolated act but the result of dynamic interactions among actors, including research institutions, farmers, government agencies, and private companies-within a given institutional and infrastructural context. According to Hall *et al.,* (2006), an innovation system comprises the organizations and individuals involved in the generation, diffusion, adaptation, and use of knowledge, as well as the rules, norms, and institutions that govern these interactions.

A well-functioning innovation system requires not just effective technologies, but also robust institutional arrangements, actor collaboration, supportive policies, and sufficient infrastructure. As such, the performance of agricultural innovations cannot be separated from the structure and dynamics of the systems in which they operate.

2.3. The Scaling Scan Framework

To operate systems thinking in scaling assessments, this study uses the Scaling Scan Framework developed by Jacobs, Ubels, and Woltering (2018). The framework identifies ten "scaling ingredients" critical to understanding and guiding scaling processes:

1. Technology/Practice – Suitability and relevance of the innovation

2. Awareness and Demand – Readiness and willingness of users
3. Business Case – Economic viability for all actors
4. Value Chain – Connectivity and effectiveness of stakeholder linkages
5. Finance – Accessibility of funding for users and actors
6. Knowledge and Skills – Capacity at both individual and institutional levels
7. Strategic Collaboration – Partnerships and multi-stakeholder alignment
8. Evidence and Learning – Data and feedback mechanisms
9. Leadership and Management – Coordination and vision
10. Public Sector Governance – Enabling policy and regulatory environment

While this framework is valuable for identifying practical barriers and enablers, it does not fully incorporate structural dimensions such as actor relationships, institutional norms, and infrastructure. Therefore, this study combines the Scaling Scan with the Innovation System approach to provide a more comprehensive analysis of maize scaling efforts in Ethiopia.

2.4. Conceptual Framework

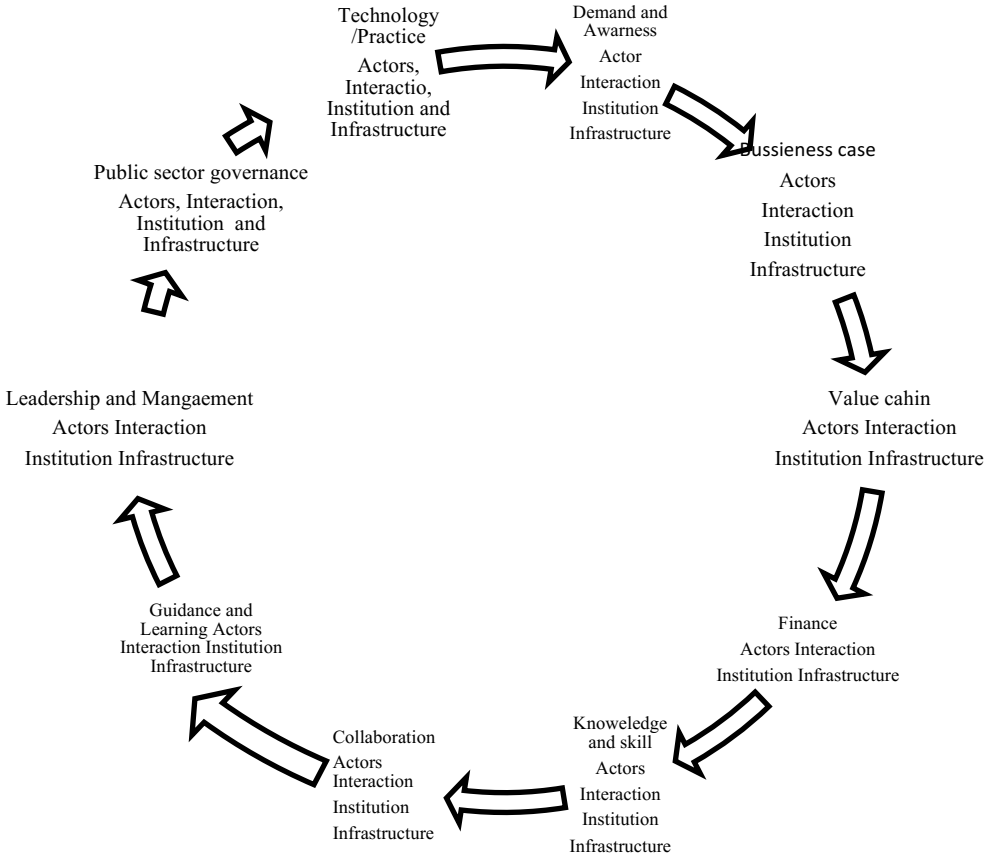
This study integrates two analytical lenses:

1. The Innovation System Perspective to assess the structural dynamics of actors, interactions, institutions, and infrastructure.
2. The Scaling Scan Framework to evaluate the operational strengths and weaknesses across the ten key ingredients necessary for successful scaling.

This dual approach enables a holistic analysis of the maize innovation landscape in Ethiopia. It allows for identification of leverage points and systemic gaps that hinder or enable the large-scale adoption of improved maize varieties.

The conceptual framework used in this study reflects the following logic:

- Successful scaling requires more than effective technology; it necessitates strong alignment between actors, clear institutional mandates, supportive policies, and sustainable financing.
- The absence of interaction, weak infrastructure, or conflicting institutional goals can block otherwise viable innovations from reaching scale.
- Combining empirical assessments of scaling ingredients with a structural analysis of the innovation system provides richer insights into real-world challenges and solutions.



2.5. Methodology

2.5.1. Research Approach

A qualitative research design was employed to investigate the institutional, systemic, and operational factors affecting the scalability of improved maize varieties in Ethiopia. The integrated framework of the Innovation System and the Scaling Scan guided the design, data collection, and interpretation.

2.5.2. Sampling technique and Data Collection

Two purposive sampling strategies were used the first one is criterion sampling: farmers were selected based on experience with improved maize varieties and over 10 years of farming. The second one is snowball sampling: key informants were identified from national, regional, and local institutions based on expert referrals. Data were collected via four Focus Group Discussions (FGDs) with 6–8 farmers in each of the selected kebeles, one FGD per kebele with development agents, and 12 key informant interviews with researchers, extension workers, and private actors.

2.5.3. Data analysis

Qualitative content analysis was used to interpret interview and FGD data. Each Scaling Scan ingredient was scored based on consensus among expert raters. Results were triangulated with narratives to validate patterns. A spider diagram and comparative matrix illustrated differences across public and private sector efforts.

3. Results and Discussion

3.1. Diverging scaling strategies

The study reveals notable differences in how public research centers and private companies such as Pioneer Hi-Bred Seeds Ethiopia Plc. prioritize, plan, and implement scaling strategies for improved maize varieties.

- Public research centers, seed enterprises and agricultural extension services in Amhara Region focused primarily on pre-scaling and demonstration activities, often in partnership with government-led initiatives such as AGP-II. However, these efforts lacked clear, long-term scaling ambitions and robust monitoring mechanisms.
- In contrast, Pioneer Hi-Bred Seeds Ethiopia Plc. adopted a market-driven approach, leveraging the Advanced Maize Seed Adoption Program (AMSAP)—a public-private partnership supported by USAID—to reach over 100,000 smallholder farmers. The company employed structured planning, resource mobilization, and policy engagement to advance scaling ambitions.

This contrast illustrates a key insight: intentional and well-financed private initiatives tend to outperform public-sector efforts in systematic scaling, though they often struggle with institutional integration and sustainability.

3.2. Comparative Analysis of Scaling Ingredients

Technology/Practice:

Farmers and institutional stakeholders overwhelmingly agreed that the P3812W (Limu) hybrid variety released by Pioneer demonstrated superior performance in terms of yield, disease resistance, and adaptability. It was more readily accepted by farmers compared to public-sector varieties like BH546.

- *(Limu)*: High compatibility with local conditions; strong farmer preference; limited availability and accessibility due to exclusive rights.
- *(BH546)*: Technically sound and widely available; however, perceived as less competitive in productivity and quality.

Awareness and Demand:

Both sectors engaged in awareness creation, but AMSAP's use of the national extension system allowed Limu to gain strong social credibility and rapid uptake.

- Limu benefitted from strong promotion efforts, field days, and the credibility of government agents.
- However, concerns emerged over seed sovereignty, with fears that reliance on imported parental stock could create long-term dependency.

Business Case and Value Chain Integration:

While AMSAP successfully created some business linkages—connecting farmers to cooperatives, unions, and buyers like the World Food Program—overall value chain development remained weak for both varieties.

- Pioneer Hi-Bred Seed Ethiopia plc., Limited supply of Limu; monopolization by DuPont Pioneer hindered local entrepreneurship.

- *Amhara research centers*: More actors involved in seed production (e.g., Amhara Seed Enterprise), but poor market linkage and demand generation for BH546.

A key insight is that supply-side innovation without corresponding market infrastructure or institutional coordination limits scaling potential.

Finance and Accessibility:

AMSAP facilitated access to microfinance and cooperative-based distribution, improving short-term affordability. However, black-market dynamics and inconsistent supply limited equitable access.

- Pioneer Hi-Bred Seed Ethiopia plc. Some financing schemes in place, but not sustained or inclusive.
- *Amhara research centers,* little to no targeted financial mechanisms for scaling; affordability less of an issue, but uptake was lower.

Knowledge and Skills:

Limu's promotion was externally driven, with little engagement from local research or education institutions.

- Pioneer Hi-Bred Seed Ethiopia plc. Strong capacity in promotion and quality control but limited local ownership or capacity-building.
- *Amhara research center*: Better integration with universities and research centers, though outreach remained weak and fragmented.

The lack of participatory research and knowledge co-creation constrained sustainability in both cases, particularly for the private variety.

Strategic Collaboration:

AMSAP involved key national actors, but excluded regional research institutions and seed enterprises, creating friction and resistance.

- Pioneer Hi-Bred Seed Ethiopia plc. Collaboration limited to a few influential partners; missing engagement with key public actors at the regional level.
- *Amhara research center:* Fragmented collaboration with overlapping mandates and unclear responsibilities.

Evidence and Learning:

There was a general lack of robust impact data across both models. Monitoring and evaluation systems were weak or non-existent, hindering adaptive learning.

Leadership and Management:

AMSAP demonstrated relatively effective leadership in scaling Limu, using decentralized government structures and clear goals.

- Pioneer Hi-Bred Seed Ethiopia plc. Clear leadership structure but lacked inclusivity.
- *Amhara research center*: Leadership fragmented; limited advocacy or strategic coordination.

Public Sector Governance:

Amhara research centers provided stronger regulatory and policy support for public varieties but were reluctant to support private innovations, particularly Limu.

- Concerns about foreign dependence and competition with domestic varieties led to passive or even obstructive roles by regional agencies.
- No enabling policy existed to support hybrid seed importation, multiplication, or collaborative production models.

3.3. Scoring Summary: Scaling Ingredients

The study used expert scoring to quantify the relative strength of each ingredient. The spider-web diagrams below illustrate these dynamics visually (included in original version).

- Amhara research center (BH546): Strong in governance, knowledge, and basic availability; weak in business case, leadership, and value chain integration.
- Pioneer Hi-Bred Seed Ethiopia plc. (Limu): Strong in awareness, farmer demand, and leadership; weak in governance support, inclusivity, and local knowledge development.

Scoring results of Scaling ingredients based on the qualitative analysis

Table 1 Scoring results of scaling ingredients for varieties released by public agricultural research centers

Scaling ingredients	Overall score	Question 1	Question 2	Question 3	Question 4
1. Technology/ practice	**5.0**	5.0	5.0	5.0	5.0
2. Awareness and demand	**3.0**	4.0	3.0	4.0	1.0
3. Business cases	**2.5**	1.0	5.0	1.0	3.0
4. Value chain	**1.0**	1.0	1.0	1.0	1.0
5. Finance	**3.3**	4.0	3.0	3.0	3.0
6. Knowledge and skills	**4.5**	3.0	5.0	5.0	5.0
7. Collaboration	**1.8**	4.0	1.0	1.0	1.0
8. Evidence and learning	**3.3**	5.0	2.0	2.0	4.0
9. Leadership and management	**1.5**	3.0	1.0	1.0	1.0
10. Public sector governance	**4.0**	5.0	5.0	5.0	1.0

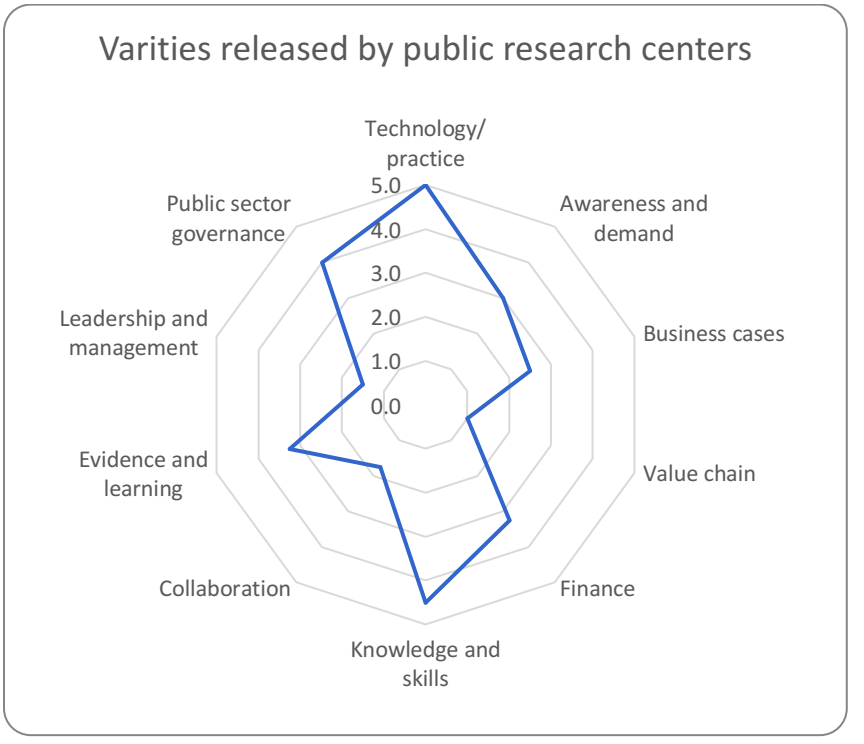


Figure 1. Scoring results of scaling ingredients for public research centers

Table 2 Scoring results of scaling ingredients for varieties released by Pioneer Hi-Bred Seeds Ethiopia Plc.

Scaling ingredients	Overall score	Question 1	Question 2	Question 3	Question 4
1. Technology/ practice	**4.8**	5.0	5.0	4.0	5.0
2. Awareness and demand	**4.3**	5.0	3.0	5.0	4.0
3. Business cases	**4.0**	4.0	4.0	4.0	4.0
4. Value chain	**2.0**	2.0	2.0	2.0	2.0
5. Finance	**3.0**	4.0	2.0	3.0	3.0
6. Knowledge and skills	**2.8**	3.0	3.0	3.0	2.0
7. Collaboration	**3.5**	5.0	4.0	3.0	2.0
8. Evidence and learning	**3.3**	4.0	3.0	3.0	3.0
9. Leadership and management	**4.3**	5.0	5.0	4.0	3.0
10. Public sector governance	**2.0**	2.0	2.0	2.0	2.0

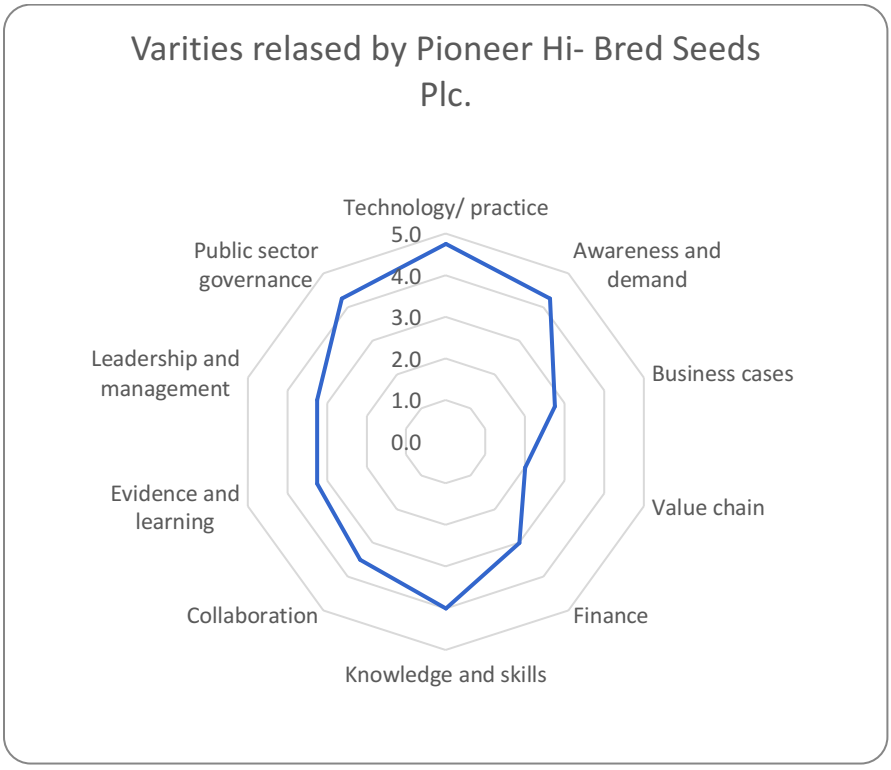


Figure 2. Scoring results of scaling ingredients for varieties released by Pioneer Hi-Bred Seeds Plc.

3.4. Key Insights

- ♣ Scaling requires institutional readiness, policy alignment, and financial access—not just strong technology only.
- ♣ Innovation exclusivity (e.g., Limu monopoly) undermines system-wide learning and adaptation.
- ♣ Fragmented actor coordination, particularly in the public sector, hinders scaling.
- ♣ Successful partnerships must be inclusive and support local innovation ecosystems.

3.5. Innovation System Analysis: Actors, Interactions, Institutions, and Infrastructure

An Innovation System analysis helps identify the structural dimensions that enable or constrain the scaling of improved maize varieties in Ethiopia. This section disaggregates the system into four core elements—actors, interactions, institutions, and infrastructure—and compares them across the two cases studied: public sector varieties (e.g., BH546) and private sector-led varieties (e.g., Limu by Pioneer Hi-Bred Seeds Ethiopia Plc.).

Key Actors and Their Roles:

- Public Sector (Amhara Research Center, Extension Services, ASE): Lead the varietal development, promotion, seed multiplication, and distribution of BH546. They have strong mandates but limited capacity for market engagement or post-harvest support.

- Private Sector (Pioneer Hi-Bred Seeds Ethiopia Plc., DuPont, Agro-dealers): Drive innovation and promotion for Limu. Focused on commercial scaling, with limited involvement in participatory research or local knowledge integration.
- Development Partners (e.g., USAID): Fund programs like AMSAP, offering resources and technical support to both sectors.
- Farmers and Cooperatives: Act as end-users and potential seed multipliers. They are more engaged with the public sector in community-based seed systems but express a preference for the Limu variety.

Interactions:

- Public Sector: Interactions are fragmented across actors, with little coordination among research, extension, and seed enterprises. Multi-actor platforms are weak or non-functional.
- Private Sector (AMSAP): Demonstrates stronger vertical coordination between Pioneer, extension agents, and selected cooperatives—but limited horizontal integration with local research institutions or regional government.

Institutions:

- Regulatory Frameworks: Favor public varieties. Policies for seed registration, multiplication, and subsidy allocation are better aligned with public institutions.
- Norms and Power Structures: There is institutional inertia favoring public-sector control, limiting the flexibility needed for private innovation. Resistance to hybrid seed monopolies is evident in regional policy discourse.

Infrastructure:

- Public Sector: Utilizes existing government infrastructure—seed labs, distribution networks, and training centers—but these are under-resourced.
- Private Sector: Builds project-specific infrastructure for seed production and distribution (e.g., AMSAP networks), but sustainability is unclear without donor support.

In summary, Pioneer's model benefits from structured planning and strong vertical links but lacks systemic inclusivity. The public model is more embedded institutionally, yet suffers from weak actor coordination, infrastructure gaps, and market integration issues.

3.6. Technical and institutional challenges and opportunities

This subsection summarizes cross-cutting challenges and opportunities to inform actionable scaling strategies.

Key Technical Challenges:

- ♣ Seed Supply Constraints: Limu's availability is restricted by exclusive licensing, while BH546 suffers from quality inconsistency.
- ♣ Knowledge Gaps: Limited agronomic training and follow-up support post-distribution, especially for Limu.
- ♣ Poor Feedback Loops: Weak monitoring mechanisms limit learning from field-level performance and adaptation.

Key Institutional Challenges:

- ♣ Fragmented Collaboration: Public sector actor's work in silos and AMSAP excludes key regional institutions.
- ♣ Policy Misalignment: No harmonized strategy exists to integrate public and private seed systems under one coherent framework.
- ♣ Weak Local Ownership: Private scaling efforts have not been domesticated into local systems, creating dependency risks.

Opportunities:

- Growing Farmer Demand: Both BH546 and Limu have demonstrated farmer interest—an essential foundation for scaling.
- Potential for Inclusive PPPs: Strengthening ties between universities, cooperatives, and private firms can democratize innovation and distribution.
- Digital Extension Tools: Could enhance awareness, training, and feedback, particularly in remote areas.
- Regional Innovation Platforms: Formalizing spaces for joint planning and review can enhance transparency and strategic alignment.

4. Conclusion and Recommendations

This study compared public and private sector approaches to scaling improved maize varieties in Ethiopia using an integrated framework. Findings reveal that while Pioneer's Limu variety excelled in productivity and farmer appeal, it lacked local integration and faced governance challenges. Public sector varieties were more inclusive but constrained by weak business models and coordination gaps. True scalability demands systemic alignment, actor collaboration, inclusive platforms, and financial and policy coherence.

Based on the findings of this study the following points are recommended:

- ♣ Establish multi-actor platforms to enable regular joint planning, coordination, and trust-building.
- ♣ Strengthen seed system integration across research centers, cooperatives, agro-dealers, and microfinance.
- ♣ Empower regional research institutions to participate in public-private partnerships.
- ♣ Decentralize seed multiplication of Limu and engage local cooperatives and universities.
- ♣ Introducing digital extension tools to share agronomic knowledge and market information.
- ♣ Develop targeted, seasonal input financing tools through banks and cooperatives.

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Progress of Honey Development Initiative in Oromia Regional State

Tolera Kumsa*[1] and Chimdo Anchala[2]

[1]Oromia Bureau of Agriculture
[2] Ethiopian Agricultural Transformation Institute
* Corresponding author: *tolekume@yahoo.com*

Abstract

Promoting improved beekeeping management can enhance food security, economic empowerment, environmental conservation, and community development through job creation and increased household income. Recognizing this potential, the Oromia National Regional State launched the Honey Development Initiative in 2020 under the Jimma Declaration, with the motto "Making Oromia a Land of Honey Sea." The initiative was implemented for five years (2020–2025) in 15 pilot zones. This assessment aimed to review its performance and outcomes using annual reports and field observations collected during the implementation period. The results show substantial progress. The supply of modern beehives increased from 47,000 in 2021 to 1.7 million in 2024, while honey production rose from 45,892 tons in 2020/21 to 117,000 tons in 2023/24. The initiative supported 300,570 beekeepers, including landless youth, with women accounting for 8% (20,471). In addition, about 285 SMEs were established and trained in frame hive production, generating approximately 1.8 billion ETB from hive production alone. Despite these achievements, demand for improved hives and higher-quality honey remains unmet due to skill gaps, limited access to accessories, low and poor-quality yields, scattered production, and weak market outlets. Therefore, it is recommended to sustain the initiative through strategic planning, integrated production packages, capacity building, producer clustering, and stronger market linkages

Keywords: Beekeeping development, Honey production, Initiative, Youths

1. Introduction

Beekeeping offers a source of income that is relatively low-cost to initiate and maintain, making it accessible to small-scale farmers and marginalized communities (Wagner *et al.,* 2019; Prodanović *et al.,* 2024). Beyond its economic benefits, beekeeping has strong potential to foster social cohesion and empower marginalized groups within rural communities, as the practice often involves collective action for sharing knowledge, resources, and marketing channels (Wagner *et al.,* 2019; Mwandifura *et al.,* 2022). Globally, honey production has been steadily increasing, reaching 1.83 million tons in 2022, with an average annual growth rate of 1.69% (Popescu *et al.,* 2024). China is the leading producer, followed by Turkey, Iran, India, and Argentina. In sub-Saharan Africa, honey production has also shown significant growth, with an estimated output of 450,000 tons in 2022, accounting for about 20% of global production (Statista, 2024).

Ethiopia is the leading honey-producing country in Africa, followed by Kenya, Sudan, Tanzania, and Uganda, which together contribute more than 80% of the continent's total honey production (Statista, 2024; FAO, 2020). Ethiopia, Kenya, and Nigeria are also the top honey exporters in Africa, gaining increasing recognition in international markets, particularly in Europe and the Middle East (Ajibola *et al.,* 2012; Amulen *et al.,* 2017). Ethiopia

has a long tradition of beekeeping and substantial potential for honey production, with approximately 10 million bee colonies and over 800 identified sources of honeybee forage (Benyam *et al.,* 2021). However, current production exploits only about 10% of the estimated national potential of 500,000 tons of honey and 50,000 tons of beeswax (Tekeba and Yeshitela, 2018). In response, the country has attracted significant investment in beekeeping, with the aim of producing 375,000 tons of honey by 2024/25. The Government of Ethiopia initiative, known as "Bounty of the Basket" (locally "Yelemat Tirufat"), has also recognized the strategic importance of honey production for food security, nutrition, economic growth, and environmental conservation.

Within this national context, the Oromia Regional State launched a honey development initiative in 2020 as part of the regional honey development plan at Jimma, under the motto "Making Oromia a Land of Honey Sea." The initiative spans five years, from September 2021 to June 2026, and aims to enhance honey production and marketing systems in the region by raising awareness among smallholder beekeepers on modern beekeeping management and practices, and by improving their livelihoods. Accordingly, this paper aims to track the progress of the initiative against its intended objectives and to propose strategic directions to address the major gaps that continue to limit the commercialization of honey production and marketing in the region.

2. Materials and Methods

This pilot initiative was carried out in 15 zones of the Oromia national regional state (Table 2). These zones are selected based on their potential for honey production and marketing. Effort is made to get an insight into the honey development initiative and results achieved during the stated period focusing on key achievements such as improved honey production, productivity and job opportunities created for the targeted beekeepers. In the process of tracking the progress of the initiative against the regional strategic objectives, we pursued reviewing of the initiative documents, and regular reports from the regional coordination office. This helped us to get background information and understand the planned targets and achieved results from the initiative. Annual reports produced by regional government were also taken as an important source of information to track the progress of the initiatives. In addition, interviews with key stakeholders involved in honey development initiatives, including zonal officials, input producers and beneficiaries have been used to provide qualitative data and insights into the progress, challenges, and outcomes of the initiatives.

A combination of both quantitative and qualitative data was used to understand the progress of the initiatives. The data collected were analyzed from the views of the project objectives using descriptive statistics and presented using charts, graphs, and visual representations.

Table 1: Number of zones and districts covered by the honey development initiatives in Oromia

No	Zones	No. of districts in the zone	No. of districts participated in initiative
1	Jima	20	20
2	Ilubabor	13	13
3	Buno Bedele	10	10
4	East Wollega	17	9
5	West Wollega	20	18
6	Kelem Wollega	10	9
7	Horo Guduru Wollega	10	8
8	West Shewa	23	19
9	Guji	15	13
10	West Guji	9	6
11	West Arsi	13	13
12	Bale	11	11
13	East Bale	7	5
14	East Harerge	20	18
15	West Harerge	15	11
	Total	**213**	**183**

3. Results and Discussions

This section presents the key results of the Oromia Honey Development Initiative based on the compiled reports, tables, and figures. The findings are organized around major thematic areas, including input supply, capacity development, beehive production and distribution, honey production and productivity, export performance, and employment and income generation. Each sub-section introduces the focus area and then discusses the evidence drawn from the corresponding tables and figures.

3.1. Beekeeping inputs supply

The provision of key beekeeping inputs and accessories required to modernize honey production. The findings show that the Oromia Bureau of Agriculture, in collaboration with relevant stakeholders, made substantial efforts to improve access to essential inputs for smallholder beekeepers.

According to the initiative assessment, a total of 43,127 m^3 of lumber was supplied to the targeted zones by the end of 2024 to support the production of modern frame beehives. In addition, critical accessories including 601 honey extractors, 325 casting molds, 1,172 smokers, and 300 veils were purchased and distributed to the pilot zones. These inputs created an important foundation for the expansion of improved beekeeping practices. However, despite this progress, the results also indicate that the rapidly growing demand for improved technologies has not yet been fully met, suggesting the need for further scaling up of input supply.

3.2. Beekeeping skill and knowledge development

This sub-section focuses on human capacity development in both hive production and beekeeping management. The results indicate that the initiative placed strong emphasis on building local technical capacity to overcome previous constraints, where modern hive production was limited to a few research centres.

Through the initiative, more than 285 Small and Micro-Enterprises (SMEs) with woodworking experience were identified and trained in modern beehive production across the 15 pilot zones. In addition, 190 beekeeping experts received Training-of-Trainers (TOT) courses delivered by researchers from Holeta Bee Research Center. These trained experts are now responsible for providing tailored training to beekeepers and supporting follow-up activities. This capacity-building effort is a critical enabling factor behind the rapid scale-up observed in hive production, distribution, and honey output in subsequent years.

3.3. Beehives production and distribution to pilot zones

This sub-section presents the scale and trend of modern beehive production and distribution under the initiative (Table 2). The results show a dramatic increase in the number of modern beehives distributed over the implementation period.

As indicated in Table 2, the number of modern beehives distributed increased from 25,000 in 2020/21 to 1,071,000 in 2023/24, reaching a cumulative total of 1,698,937 beehives. This represents more than a 60-fold increase from the first year to the fourth year of implementation. Out of the total distributed beehives, 263,277 were directly contributed by the initiative at a highly subsidized cost, while 1,435,660 were supplied by other stakeholders engaged in apiculture development.

This result clearly demonstrates the strengthened production capacity of local SMEs and the growing involvement of partners in scaling up improved beekeeping technologies. The sharp increase in hive availability also explains the subsequent rise in honey production and productivity observed in later sections.

Table 2: Distributed improved beehives by the initiatives

Year	Unit	Modern beehives distributed by the initiative	Modern beehive distributed by stakeholders	Total
2020/21	No.	25,000	-	25,000
2021/22	No.	51,500	-	51,500
2022/23	No.	69,445	481,992	551,437
2023/24	No.	117,332	953,668	1071000
Sub-total	No.	**263,277**	**1,435,660**	**1,698,937**

3.4. Improved volume of honey production in Oromia region

This sub-section analyses trends in honey production at regional and pilot-area levels using. The results show a strong and consistent upward trend in honey output during the initiative period.

As shown in Figure 1, total honey production in Oromia increased from about 66,261 tons in 2020 to approximately 117,000 tons in 2024. This steady growth indicates a substantial improvement in regional honey production capacity. The main drivers of this increase include the shift from traditional to improved beekeeping systems, better access to modern beehives, and favourable conditions created by environmental rehabilitation and green legacy initiatives.

According to the annual reports from the Oromia Bureau of Agriculture, the volume of honey production from traditional, transitional and frame beehive has increased significantly in the region. (Figure 1). For instance, the volume of honey, which was 66,261 tons in 2020 has potentially increased to 117,000 tons in 2024, showing a consistent upward increase in honey production from year to year. The main factors for such increased trend in honey production is reported to be the shift from traditional beekeeping system to improved beekeeping management by beekeepers, availability of immense potential for honey production related with green legacy initiatives, and improved accessibility and adoption of modern beehives by beekeepers showing the contribution of the initiatives in laying strong foundation to increase honey production in the region.

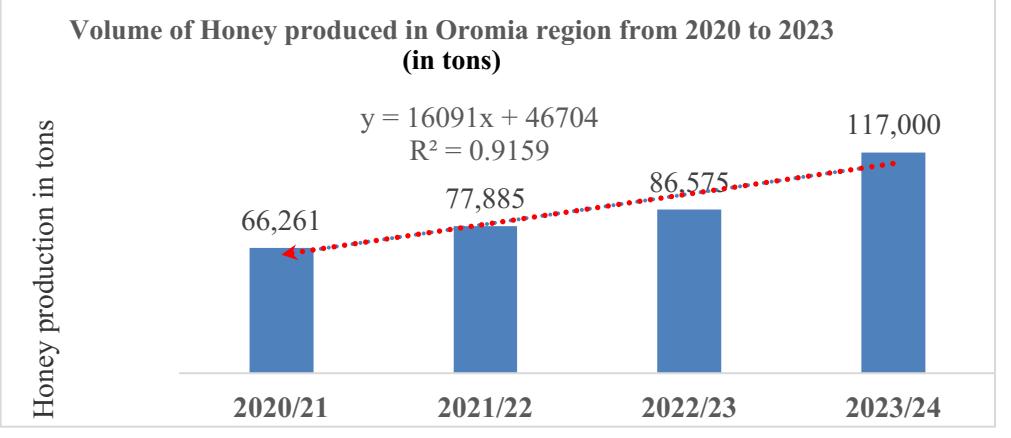

Figure : The total volume of honey produced with the support of the Oromia Honey Development Initiative between 2020 and 2024.

In same way, Figure 2 shows an even more striking increase in honey production from modern beekeeping. Production rose from 625 tons in 2021 to 26,775 tons in 2024, reflecting the rapid adoption of improved hives and management practices. Furthermore, the results indicate that trained beekeepers achieved higher yields per hive: in Jimma and West Shewa, trained beekeepers harvested about 30 kg and 23 kg per hive, respectively, while untrained beekeepers harvested only 17 kg and 15 kg per hive. This clearly demonstrates that productivity gains are driven not only by access to modern hives but also by improved skills and management practices.

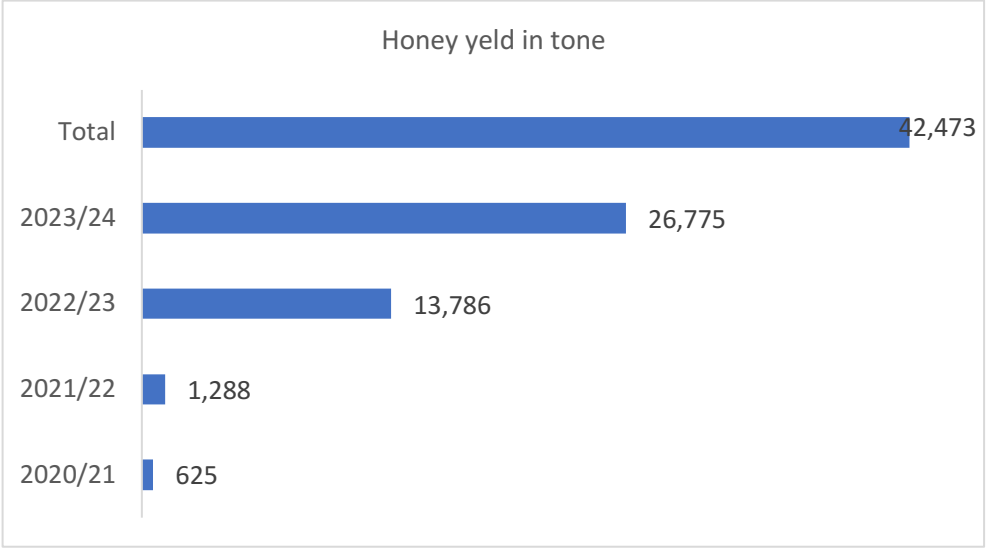

Figure 2: Volume of honey produced from modern beekeeping through the support of the initiative from 2021 to 2024.
Source: Compiled from report on honey development initiative

3.5. Honey productivity

This sub-section focuses on differences in productivity across hive types and management systems. The results show that honey productivity is strongly influenced by the type of beehive, agro-ecology, and colony management practices.

On average, traditional hives produce about 7 kg of honey per hive per year, whereas modern hives yield approximately 24–28 kg per hive per year. In addition, modern hives allow two to three harvests per year, depending on local conditions and management skills, while traditional hives are usually harvested only once per year. These findings reinforce the results shown in Figures 1 and 2, confirming that the shift to improved beekeeping systems and better seasonal colony management—such as timely supering, super reduction, harvesting, and supplementary feeding—plays a central role in increasing both productivity and total production

3.6. Organic Honey Export Performance

This sub-section presents results related to honey export performance. According to reported data, Oromia is leading other regions in organic honey exports, contributing 31.5 metric tons out of the national total of 37.8 metric tons (UNDO,2024). This result indicates that the initiative is not only increasing production but also strengthening the region's contribution to export markets, particularly for organic honey. The growing export share suggests improvements in quality, volume, and market orientation of honey production in the region.

3.7. Employment Creation and Income Generation

Creating employment opportunities is one of the objectives of the honey development initiative in the region. Accordingly, the implementation of the initiatives in pilot areas has

motivated both women and youth to actively participate in bee keeping business. The contribution of the initiative to job creation and income generation shown in Table 3. The results show that the initiative generated substantial employment opportunities along the honey value chain.

A total of 1,425 jobs were created for SME members, and 2,850 jobs were created within SMEs engaged in beehive manufacturing. In addition, 425,587 beneficiary-level jobs were created over the four years, bringing the total number of jobs generated to 429,862. Overall, 300,570 smallholders were directly engaged in honey production and marketing using improved beehives, of whom about 8% (20,471) were women. Moreover, more than 20,000 landless youth were organized into beekeeping groups and began honey production integrated with watershed management and forest conservation.

In terms of income generation, the results show that about 1.87 billion ETB was generated from frame beehive production, and approximately 4.82 billion ETB is expected from honey sales by the end of the initiative period. These figures demonstrate the strong contribution of the initiative to household income growth and value chain development.

Table 3: Employment created from the initiative

Descriptions	Unit	2020/21	2021/22	2022/23	2023/24	Total
Job created for SME members	No.	735	250	250	190	1,425
Job created in SME	No.	1470	500	500	380	2,850
Job created for beneficiaries	No.	5,000	10,300	110,287	300000	425,587
Sub-total	No.	**7,205**	**11,050**	**111,037**	**300,570**	**429,862**

Source: Reginal honey development initiative report 2024

4. Conclusion and Recommendations

The results of the Oromia Honey Development Initiative demonstrate that the program made a meaningful contribution to expanding beekeeping activities, improving access to modern inputs, increasing honey production and productivity, and creating employment opportunities along the honey value chain. The broad geographic coverage and substantial input distribution laid a strong foundation for production growth, while the observed increases in output and productivity indicate that technology adoption and capacity-building efforts were effective.

The evidence from this study leads to several important conclusions about the role of apiculture in agricultural transformation and rural development in Oromia. The results imply that the shift toward improved beekeeping systems represents more than a technological change; it reflects a structural transformation in production practices that can support commercialization and diversification of rural livelihoods. This suggests that apiculture should be treated as a strategic agribusiness sub-sector rather than a marginal livelihood activity.

The findings also indicate that productivity gains depend fundamentally on human capital and management quality. Technology alone is insufficient to sustain performance improvements without continuous technical support and effective extension services. This

underscores the need to view capacity development as a core investment area, not as an auxiliary intervention, if productivity improvements are to be maintained and expanded over time.

In addition, the results imply that production growth must be matched with stronger market integration and quality orientation. Without coordinated value chain development, increases in output risk translating into price volatility and uneven income gains. The emerging role of Oromia in higher-value markets shows the potential returns to market-oriented strategies, but also highlights the importance of institutional arrangements that link producers, enterprises, and buyers more effectively.

Finally, the findings suggest that apiculture has strong potential as an inclusive employment and enterprise development pathway, particularly for youth and small enterprises. However, sustaining these impacts requires moving from time-bound project support to more institutionalized systems that integrate technology supply, skills development, enterprise support, and market access in a coherent framework.

Based on the results, the following recommendations are proposed:

- Consolidate and strengthen the supply system for modern beekeeping technologies by coordinating support to local manufacturers and suppliers, improving quality assurance, and aligning production more closely with effective demand, so that technology adoption can continue in a sustainable and cost-effective manner.
- Reorient extension and capacity development toward continuous, practice-based support with strong emphasis on seasonal colony management, productivity improvement, and quality handling, recognizing that skills and management are decisive drivers of performance rather than secondary inputs.
- Promote more integrated, market-oriented value chain development by strengthening producer organizations, supporting collective marketing and basic processing, and improving linkages between producers, enterprises, and buyers, in order to stabilize market access and strengthen incentives for quality production.
- Combine enterprise development and inclusion strategies by expanding support to SMEs, youth, and women through improved access to finance, business development services, and market information, ensuring that employment creation and income gains are both scalable and sustainable.
- Strengthen monitoring and learning systems and use performance evidence more systematically for targeted technical and institutional support, so that productivity and market performance gaps across areas can be addressed in a timely and cost-effective manner

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Adaptation and Participatory Evaluation of Improved Bread Wheat Varieties under Irrigation towards Technology Promotion in the Dry Low- and Mid-land Parts of Waglasta areas, Ethiopia

Kndalem Yaregal Mersha*, Abebe Assefa, Getawey Girmay, and Netsanet Asefa

Amhara Agricultural research Institute, Sekota Dryland Agricultural Research Center, P.O. Box 62 Sekota, Ethiopia
*Corresponding author: kndalemy@gmail.com

Abstract

*Wheat production in Waglasta's arid regions is susceptible to environmental stress. With the help of farmers, the experiment was carried out to assess and promote heat-tolerant and midland improved wheat varieties, raising demand and awareness in the target areas. Twenty-two types of bread wheat were assessed in 2021 during the irrigation season: eight in Abergele's lowland regions and 14 in Sekota's midland regions. A random whole block design with three replications was used for both sets. Using a simple block design with 10*10m2 plot sizes in the 2023 irrigation season, four varieties—Gambo and Fentale-2 from the lowlands and Adet-1 and Kakaba from the midlands—as well as the Sekota-1 (check) variety were developed for the participatory technology promotion program at Sekota and Lalibela districts. In both areas, 43 members of farmers' research extension groups were purposefully selected, with more than 20% of these groups being led by women. In most of the attributes, the performance of the varieties in the two sets revealed a highly significant difference ($p < 0.01$) between treatments. Fentale-2 consistently performed well in yield and related traits; grain yield in adaptation and promotion programs was 1962.8 kg/ha and 2960 kg/ha, respectively. Additionally, in both areas, the farmers prioritized Fentale-2 over various other varieties. As a result, the Fentale-2 variety can be pre-scaled up and recommended for irrigated wheat production in Abergele, Sekota, Lalibela, and similar agroecologies.*

Keywords: Farmer-led selection, Heat-tolerant varieties, Irrigated cropping systems, Semi-arid agroecologies, Variety pre-scaling

1. Introduction

With 770.9 million tons produced on 219 million hectares of land, wheat is the most frequently grown cereal crop in the world and accounts for 8% of global primary crop commodity production (FAO, 2023). Next to South Africa, Ethiopia is one of the largest producers of wheat in Africa. Over 4 million smallholder farmers in Ethiopia, who grow 14.62% of the nation's grain crop area, produce wheat - the fourth largest cereal crop (CSA, 2021). In Ethiopia, about 4.5 million smallholder farmers cultivate wheat on 1.9 million hectares of land; in the Amhara region, 1.9 million smallholder farmers cultivate wheat on over half a million hectares of land. The region's average production is 2831 kg/ha, while the nation's is 3046 kg/ha (CSA, 2021). Wheat grows mostly in the mid- and high-land areas (altitude ranges from 1900 to 2700 m a s l), which have adequate rainfall (Tariku *et al.*, 2022). In recent years, Ethiopia initiated projects to scale out wheat production in the lowland and midland areas under off-season production. Five percent of the nation's 3.7 million hectares of potential irrigable land has been irrigated (Descheemaeker, 2014).

Ethiopia has more access to and potential for irrigation throughout the country, especially in the lowlands, but the country's economic share is reduced when this potential is not fully utilized (Hordofa *et al.*, 2008). Although the household's income has not yet increased, the production of bread wheat under irrigation has a positive effect on livelihoods by diversifying each household's nutritional consumption (Nigussie *et al.*, 2015). The importance and demand for wheat products are expected to double in the future; this might worsen the import burden on the country. It is also an important staple food crop in Ethiopia; 12% of daily per capita consumption accounts for 75% of the population in the diets of several Ethiopians, providing about 15% of the caloric intake for the country's over 90 million population (FAO, 2015; Descheemaeker, 2014). In addition to being an industrial input for pasta and macaroni products, wheat is utilized as the primary native ingredient in enjera, qolo, tella, dabokolo, genfo, and bread (Nigussie *et al.*, 2015). In addition, agro-pastoralist cultures use wheat straw as animal fodder. Climate change-related factors that threaten wheat cropping include new and more aggressive pests and diseases, declining water supplies, a shortage of available land, and unpredictable weather patterns (CIMMYT, 2016). As a result, the Ethiopian government places more emphasis on raising wheat market connectivity and enhancing wheat crop productivity during both irrigation and rain-fed production seasons (IFPRI, 2015). Therefore, by 2025, the government intends to replace the import of wheat products with locally produced products, potentially saving almost USD 3 million in foreign exchange. The government is working to increase wheat yield by growing crops in a variety of agroecologies, including the country's arid lowlands, with impressive results.

According to Grandgirard *et al.* (2002), there are a number of benefits to participatory technology review, including increased crop productivity and production, a quicker rate of variety adoption, and easier access to information and empowerment for farmers. Participatory rural evaluation, participatory variety technologies, and evaluating the need and availability of land races in the hands of farmers are methods of improved varieties to be promoted and embraced by the farmers (Witcombe *et al.*, 1996). Even though wheat is necessary for a variety of household food preparation items, there is still an imbalance between supply and demand, forcing the nation to import wheat products for a considerable amount of time using foreign currency. The problem of low wheat production and productivity potential in the country was associated with soil fertility and erratic rainfall specifically and biotic and abiotic stress (Kidane *et al.*, 2023). Ethiopian wheat production is susceptible to environmental stressors such drought, low soil fertility, and the prevalence of pests and diseases in the dry lowland and midland regions of Waglasta. These challenges are further exacerbated by climate changes, which threaten food security and the livelihoods of smallholder farmers in the areas. Improved bread wheat varieties have been developed and marketed in various regions of Ethiopia, but their effectiveness and uptake in agroecologies under moisture stress, such as Waglasta, are still restricted. There is a significant issue with the adaptation and participatory assessment of improved bread wheat varieties, as well as data on the effectiveness of advanced bread wheat varieties under irrigation in the arid low- and mid-land regions of Waglasta, despite national attempts to increase wheat production.

The conventional wheat varieties that farmers in these regions mostly use are low-yielding and vulnerable to both biotic and abiotic stressors. Additionally, there are not many high-yielding, stress-tolerant, regionally adapted wheat varieties that can flourish in the region's

irrigation condition. Furthermore, poor adoption rates result from extension services frequently promoting innovations without enough farmer involvement. Improved wheat varieties that are irrigated under these conditions must be found and promoted. Therefore, the primary objectives of this research were to evaluate, choose, and promote improved and heat-tolerant wheat varieties with farmer engagement, thereby raising awareness and demand for the new wheat varieties in the target locations.

2. Materials and Methods

2.1. Description of the study areas

During the 2021 irrigation season, the adaptation trial was carried out in the midland area of Sekota (Woleh or set II) and the lowland area of Abergele (Belitarif or set I). Abergele is situated at 12°, 53', 43.05'' N and 38°, 56', 39.76'' E with an elevation of 1334 m.a.s.l., while Lalibela is situated at 12°, 03', 05.24'' N and 39°, 02', 27.62'' E with an elevation of 2177 m.a.s.l. (Figure 1). Rugged topography, inadequate rainfall, degraded land, little greenery, and a low capacity to retain moisture are characteristics of these regions (Melak *et al.*, 2024). In addition to this, market access is further restricted by inadequate infrastructure and few connections to value chains. Because of their accessibility to irrigation water and representativeness of the dry low- and mid-land agroecologies, Lalibela, Abergelle, and Sekota were chosen as trial sites. These regions are perfect for wheat trial sites since they are investing more in small-scale irrigation projects (Dagnachew *et al.*, 2021).

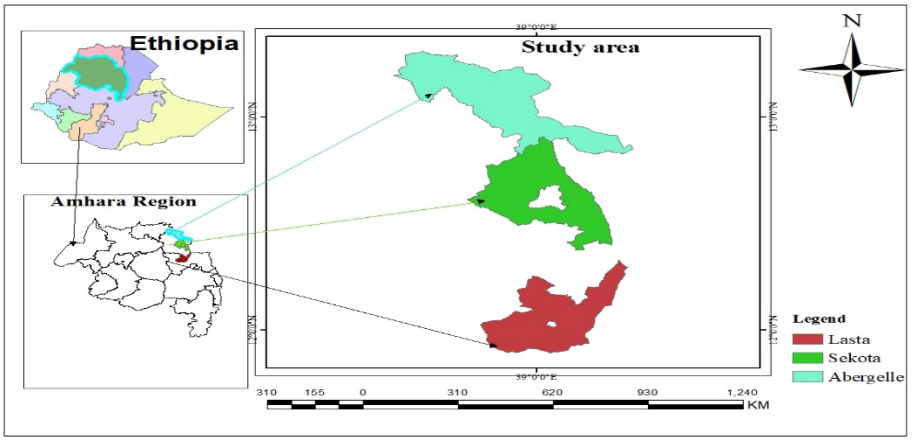

Figure 1: Map of the experimental areas

2.2. Planting materials

Two sets of 22 commercially available bread wheat varieties were assessed at two different locales. Eight of these were released as heat-tolerant varieties for the irrigation producing season after being assessed in Abergele's lowland area. In the 2021 irrigation seasons, which were published for rain-fed production seasons, the remaining 14 types were assessed in the midland region of Sekota. Based on the traits of the varieties and their agroecological range, several sets of experiments were carried out (Table 1).

Table 1: List of released bread wheat varieties

Genotype	Year of released	Target agroecology	Released for	Source	Testing area for	
					Adaptation	PTE
Amibara1	2015	Lowland	Irrigation	Werer	Abergele	
Amibara2	2017	Lowland	Irrigation	Werer	Abergele	
Ardi	2019	Lowland	Irrigation	Werer	Abergele	
Fentale1	2015	Lowland	Irrigation	Werer	Abergele	
Fentale 2	2017	Lowland	Irrigation	Werer	Abergele	Sekota, Lalibela
Gambo	2011	Lowland	Irrigation	Werer	Abergele	Sekota, Lalibela
Luci	2013	Lowland	Irrigation	Werer	Abergele	
Werer 2	2013	Lowland	Irrigation	Werer	Abergele	
Alidero	2007	Midland	Rain-fed	Holeta	Sekota	
Adet -1	2020	Mid/highland	Rain-fed	Adet	Sekota	Sekota, Lalibela
Deka	2018	Low/midland	Rain-fed	Kulumsa	Sekota	
Danda'a	2010	Mid/highland	Rain-fed	Kulumsa	Sekota	
Netsanet	2020	Mid/highland	Rain-fed	Sirinka	Sekota	
Hibist	2018	Mid/lowland	Rain-fed	Sirinka	Sekota	
Hidasie	2012	Mid/highland	Rain-fed	Kulumsa	Sekota	
Kakaba	2010	Low/midland	Rain-fed	Kulumsa	Sekota	Sekota, Lalibela
Kingbird	2015	Highland	Rain-fed	Kulumsa	Sekota	
Lemu	2016	Highland	Rain-fed	Kulumsa	Sekota	
Ogolicho	2012	Midland	Rain-fed	Kulumsa	Sekota	
Sorra	2013	Moisture deficit	Rain-fed	Sirinka	Sekota	
Tay	2005	Mid/highland	Rain-fed	Adet	Sekota	
Wane	2016	Mid/highland	Rain-fed	Kulumsa	Sekota	
Sekota-1	2013	Moisture deficit	Rain-fed	Sekota		Sekota, Lalibela

2.3. Experimental Design and Procedure

Randomized complete block design (RCBD) with three replications was used to build up both sets of the experiment. Plots had an area of 3*1.2 m2, and replications and plots were separated by 0.5 and 1 m, respectively. Both trial sets were sown using row planting systems spaced 0.2 meters apart. In accordance with crop requirements and recommendations, all agronomic techniques were applied uniformly and appropriately. The midland (Sekota) and lowland (Abergele) experimental sets received irrigation at intervals of 7–10 days and 5–7 days, respectively. The area was watered using a furrow irrigation system, and water came from the river by canal outlets all the way up to the station. Each plot's water intake was determined by manually testing the soil's moisture content and visually assessing its textures using the soil-pressed method. The fertilizer rates were taken straight from the districts' main-season wheat production package. These led to the application of 50 kg/ha of urea (split application at the knee stage of plant height and at the sowing stage) and 100 kg/ha of NPS for the experiment in the adaptation trials.

2.4. Data Collection

2.4.1. Phonological and growth stage traits

The data for heading was recorded as the number of days from crop emergence to 50% he ading, as measured in observation. It is expressed in days to heading.
Days until grain fullness (days): this was the interval between the days until maturity and th e days until heading.
The number of days until physiological maturity (days) is the number of days in the crop de velopment period between the emergence and 95% of the crop maturity stage.
The average height of ten randomly selected plants was measured from the ground to the t ip of the panicles out of the awns at the end of the crop growth time (maturity stage). The plant height (cm) was computed from this measurement.

2.4.2. Yield and yield component traits

The average height of ten spikes in each plot, measured from the base of the spike to the final order of the spikelet (except from awns), is known as the spike length (in centimeters). Ten typical spike seeds from the plot were counted, and the average result was used to determine the number of seeds per spike. At the time of harvest, the entire aboveground portions of each plot's four middle rows were weighed to determine the biomass yield (kg/ha). The weight of a thousand seeds from each experimental plot was measured in grams. Grain yield (kg/ha): when the moisture content of the seed reached 12%, the grain yield, which was initially recorded from each plot and quantified in grams per plot, was expressed as kilograms per hectare.

2.5. Participatory technology evaluation (PTE)

2.5.1. Experimental site and materials

During the 2022–2023 irrigation season, the trial was carried out in the districts of Lalibela (Medage) and Sekota woreda (Woleh). From the two adaptation trials, about five (5) kinds were chosen for additional study using a participatory technology evaluation (PTE) method. Kakaba and Adet-1 were chosen from the midland set Sekota (Woleh), whilst Fentale-2 and Gambo were chosen from the lowland set (Abergele). The usual check for both Sekota and Lalibela locations was the Sekota-1 variety.

2.5.2. Experimental design and procedures

A 10*10m2 plot size was utilized in both locations for the participatory technology evaluation (PTE). A simple (single) block with five plots spaced one meter apart and 0.2 meters between rows made up the experimental design. Every agronomic procedure was carried out equally and suitably in accordance with guidelines and crop requirements. A furrow irrigation system was used to apply irrigation to both districts at intervals of seven to ten days. The water in both places came from the river and traveled through canal outlets to the experiment station. Each plot's water intake was determined by manually testing the soil's moisture content and visually assessing its textures using the soil-pressed method. The fertilizer rates were taken directly from the districts' main-season wheat production package. These led to the use of 50 kg/ha of urea and 100 kg/ha of NPS (split application at sowing and knee stage of the plant height).

2.5.3. FREG establishments and selection criteria

In the districts of Lalibela (Medage) and Sekota (Woleh), two FREGs were created. The FREGs were purposefully chosen to include 20% female-headed members in both locations that participated in the technology evaluation and selection program on color preference, full endosperms for flour, and other desirable traits. The group members in both districts were chosen on the recommendation of the development agents (DA) and key informers. The chairman and secretary, who oversee all FREG activities with researchers and extension agents in every trial district, are also members of the organization. The technology evaluation timeline and selection procedures were explained to the FREG members. The researchers and extension agents just assisted and guided these group members as they created their own action plan. To assess and choose their best variety for the districts, the FREG members in each district conferred with one another and established selection criteria. For every variety, the following ranking criteria were established: very good, good, neutral, poor, and very poor. Fortunately, the farmers cited the same criteria: in both districts, priority was given to vegetative performance, tiller capacity, spike length, and earliness.

2.6. Statistical Analysis

To determine the degree of significance between genotypes for each attribute, analysis of variance (ANOVA) was calculated. Gen Stat 18th edition (64 bit) was used to do an analysis of variance on all the quantitative data. Fishers protected least significant difference (LSD); means were compared using 1% and 5%, even though ANOVA had shown that genotypes differed in the characteristics. Simple descriptive statistics were used to analyze all the quantitative data from the promoted activities. The pair-wise ranking method was used to determine the farmer's variety selection criteria in each district, and a weighted ranking matrix table was used to rank the criteria.

3. Results and Discussion

Due to the distinct sets of experimental materials used in Abergele woreda (Belitarif kebele) and Sekota (Woleh), the analysis of variance for yield component and grain yield was completed independently in each location.

3.1. Phonological Traits

Days to heading and maturity features showed a highly significant difference ($P<0.01$) between genotypes in heat-tolerant (Abergele) and midland (Sekota) regions, according to the analysis of variance. All varieties headed in Abergele in less than two months, according to the analysis of variance. According to these findings, eight lowland wheat types have 50% heading dates ranging from 48 to 57 days, with an average heading date of 52 days. Of them, the Werer 2 (56 days) variety took a long time to head, whereas the Ardi (44 days) type reached quickly, which was associated to Yohannes *et al.* (2023), and Degife and Demis, (2020). The average heading date at Sekota was 69 days, with 50% days to heading ranging from 62 to 78 days. In this series of experiments, Lemu (78 days) takes a long time to head, while Deka (62 days) takes a short time. This study supported the findings of Yohannes *et al.* (2023), who found that in lowland and midland regions, Ardi and Deka varieties head earlier than other types. In terms of days to heading, the Ardi (68 days) variety matured earlier than the Fentale 1, Gambo, and Werer 2 (85 days) varieties, which took a long time to mature

physiologically. The Ogolicho (103 days) variety had the earliest maturity date, while the Alidero (114 days) variety took a long time to mature in the midland and heat-tolerant sets, respectively (Table 2 and 3). Early maturing varieties are not always accurate because the yield is determined by the maturity dates. This is because yield-related features and environmental climate conditions, such temperature, have a significant impact on maturity and yield. Temperature increases during wheat's grain filling time decrease crop maturity times and reduce genotype yield potential (Islam & Wardlawb, 1978). Additional research by Tatek Tamiru *et al.* (2023) revealed that environmental factors like the rainy season's temporal and spatial variability, as well as varietal selection and sowing timing, are important determinants of wheat crop output in irrigated wheat production.

3.2. Yield and yield related traits

The plant height trait showed highly significant ($P<0.01$) and significant variations ($P<0.05$) between varieties in sets of trials in Abergele and Sekota, respectively, according to the analysis of variance. Amibara 2 and Ardi reported the shortest plant height (69 cm) at Abergele, while Hidasie and Lemu recorded the shortest plant height (61 cm) at Sekota (Tables 2 and 3). On lowland (Abergele) and midland (Sekota) settings, the Fentale 1 (82 cm) and Tay (74 cm) types had the longest plant heights, respectively. Because different genotypes of wheat exhibit distinct physiological and ecological responses to the irrigation environmental conditions, there can be significant variation in the crop's growth habit, particularly throughout the irrigation production season (Mihratu *et al.*, 2018; Raza, 2018). Fentale1 (7152.8 kg/ha) had the highest biomass output in the lowland set, followed by Amibara 1 (6805.6 kg/ha) and Gambo (6666.7 kg/ha), while Ardi (4270.8 kg/ha) had the lowest biomass yield (Table 2). Following crop harvest, grain yield and thousand seed weight were measured when the kernel's moisture content reached 12.5%. The genetic variety of wheat had a significant impact on the thousand seeds' weight. Yohannes *et al.* (2023) reported similar results. According to Shahwani *et al.* (2014), the genetic composition of the variety has a significant impact on thousand seed weight, meaning that different wheat types have varying values. A thousand seeds had mean weights ranging from 29.667 to 42 g. Based on this, the variety Gambo (42.333 g) and Werer 2 (29.667 g) were found to have the highest and lowest thousand seed weights. These results are consistent with the findings of Degife & Demis (2020), who stated that the weight of a thousand seeds ranges from 25 g to 46.67 g. According to the analysis of variance for grain yield, there was a highly significant difference ($P<0.01$) between the wheat varieties. The Gambo (2043.8 kg/ha) variety had the highest yield gain, followed by the Fentale 1 (1987.8 kg/ha) and Fentale 2 (1962.8 kg/ha) varieties. The Werer 2 (962.5 kg/ha) and Lucy (1198.6 kg/ha) varieties had the lowest yield. The Gambo variety was ranked highest in the Degife & Demis (2020) study, followed by the Lucy variety; nonetheless, Lucy produced the lowest yield (Table 1). The Sora variety produced the most biomass (4790 kg/ha) in the midlands, while the Lemu variety produced the least (3046 kg/ha). The findings of Bayissa *et al.* (2023) support this conclusion: lowland bread wheat varieties performed differently for grain yield in various agroecologies and growing seasons throughout the irrigation production season. The Wane (43g) variety had the highest thousand seed weight, followed by the Hidasie (42g) variety, while the Tay (23g) variety had the lowest thousand seed weight (Table 3). The Sora variety had the highest mean grain yield (1719.8 kg/ha), followed by Tay (1597.6 kg/ha) and Deka (1589.6 kg/ha), compared to the lowest yielding Alidero (580.2 kg/ha) and the other varieties (Table 3). The analysis of variance for grain yield revealed highly significant differences ($P < 0.01$) among

varieties. This result supported the findings of Mekonnen *et al.* (2017), who found that in rain-fed moisture stress locations, the Sora (3341 kg/ha) variety performed well and produced a high yield with appropriate genotypes in a variety of conditions. In contrast, the Alidero variety performed well throughout the rainy season in the highland regions of Dabat's northwest, according to Degenet *et al.* (2021). This suggests that temperature variations had a significant impact on the variety; a rise in temperature from 25 to 30 °C had a higher impact on the crop's grain filling time (Islam & Wardlawb, 1978).

Table 2: Mean grain yield and other agronomic traits of eight lowland heat tolerant wheat varieties tested in waghimra zone at Abergele woreda (Belitarif) in 2020/21

varieties	DH	DM	PH (cm)	SL (cm)	SPS	BM (kg/ha)	TSW(g)	GY (kg/ha)
Amibara 1	55b^{c}	82^{ab}	80^{ab}	9^{abc}	46^{a}	6805.6^{a}	40^{ab}	1492^{a}
Amibara 2	48^{e}	70^{c}	69^{d}	8^{bc}	36^{abc}	4444.4^{bc}	33^{bc}	1169.1^{bc}
Ardi	44^{f}	68^{c}	69^{cd}	8^{c}	32^{bc}	4270.8^{c}	40^{ab}	1155.2^{bc}
Fentale1	55^{abc}	85^{a}	82^{a}	10^{a}	45^{a}	7152.8^{a}	38^{ab}	1987.8^{a}
Fentale 2	51^{d}	78^{b}	76^{abc}	9^{ab}	38^{abc}	6250^{a}	42^{a}	1962.8^{a}
Gambo	54^{c}	85^{a}	76^{abcd}	10^{a}	41^{ab}	6666.7^{a}	42^{a}	2043.8^{a}
Lucy	57^{a}	78^{b}	74^{bcd}	8^{c}	37^{abc}	6111.1^{a}	36^{abc}	1198.6b^{c}
Werer 2	56^{ab}	85^{a}	70^{cd}	8^{bc}	30^{c}	5902.8^{ab}	29.667^{c}	962.5^{c}
Mean	52	79	74.875	9.175	38.242	5950.5	37.74	1496.5
LSD (5%)	**	**	**	*	*	**	*	**
Cv (%)	1.6	3.37	5.41	10.08	16.6	14.34	11.99	13.57

Where, DH-Days to Heading; DM – Days to Maturity; PH- Plant Height; SL – Spike Length; SPS- Seed Per Spike; BM- Biomass TSW- Thousand Seed Weight; GY- Grain Yield

Table 3: Mean grain yield and other agronomic traits of fourteen midland wheat varieties tested in waghimra zone at Sekota woreda (woleh) in 2020/21

Varieties	DH	DM	PH (cm)	SL (cm)	SPS	BM (kg/ha)	TSW(g)	GY (kg/ha)
Alidero	77^{a}	114^{a}	69^{abc}	9^{a}	45^{ab}	3118^{d}	34^{ab}	580.2^{f}
Adet-1	73^{b}	109^{cde}	66^{bcd}	7^{bcd}	40^{abcde}	3650^{bcd}	36^{ab}	1132.3^{de}
Deka	62^{f}	105^{ghi}	68^{abcd}	7^{cd}	39^{abcde}	4114^{abc}	39^{ab}	1589.6^{ab}
Danda'a	71^{bc}	111^{bc}	66^{abcd}	7^{cd}	42^{abc}	3948^{abcd}	40^{ab}	1229.2^{cd}
ETBW6753	67^{cde}	108^{cdef}	72^{ab}	7^{d}	41^{abcd}	4246^{ab}	41^{ab}	1458^{bc}
Hibist	65^{ef}	106^{fghi}	64^{cd}	7^{cd}	39^{abcde}	3457^{bcd}	39^{ab}	1324.7^{cd}
Hidasie	69^{bcd}	110^{cd}	61^{d}	7^{d}	39^{abcde}	3654^{bcd}	42^{a}	1195.5^{de}
Kekeba	66de	107d^{efg}	67^{abcd}	8^{bcd}	35de	3960^{abcd}	38^{ab}	1461.1^{bc}
kingbird	65^{def}	104^{hi}	62^{cd}	7^{d}	38^{bcde}	3341^{bcd}	32^{bc}	1281.9^{cd}
Lemu	78^{a}	113^{ab}	61^{cd}	8^{ab}	39^{abcde}	3046^{d}	36^{ab}	969.7^{e}
Ogolicho	65^{def}	103^{i}	68^{abcd}	8^{abc}	34^{e}	3162^{cd}	37^{ab}	1210.1^{de}
Sora	67de	107^{defg}	72^{ab}	7^{bcd}	36^{cde}	4793^{a}	40^{ab}	1719.8^{a}
Tay	72^{b}	110^{cd}	74^{a}	8^{abcd}	38^{abcde}	4772^{a}	23^{c}	1597.6^{ab}
wane	65^{ef}	107^{efgh}	66^{abcd}	7^{d}	45^{a}	4141^{ab}	43^{a}	1125de
Mean	69	108	67	7	39	3814	37.316	1276.8
LSD (5%)	**	**	*	**	*	**	*	**
CV (%)	3.18	1.6	7.05	7.96	11.09	14.92	15.79	11.29

Where, DH-Days to Heading; DM – Days to Maturity; PH- Plant Height; SL – Spike Length; SPS- Seed Per Spike; BM- Biomass TSW- Thousand Seed Weight; GY- Grain Yield

3.3. Participatory technology evaluation (PTE)

3.3.1. Grain and Biomass Yield

The primary concerns of farmers and stakeholders who have the power to accept or reject new technology are grain yield and biomass yield (Mihiretu, 2020). Grain yield and biomass attributes varied significantly, suggesting that the varieties performed differently in terms of yield and biomass. The Fentale-2 variety produced the maximum yield (2960 kg/ha) in the combined mean, whereas the lowest yielding varieties were Kakaba (1960 kg/ha), Adet-1 (2480 kg/ha), Gambo (2360 kg/ha), and Sekota-1 (2280 kg/ha), which came in second, third, and fourth, respectively. In addition to grain yield, there was a notable variation in biomass yield between the varieties; as figure 2 illustrates, the Fentale-2 variety produced the highest yield (6560 kg/ha), while the Kakaba variety produced the lowest (5040 kg/ha). In Sekota (Woleh) and Lalibela (Medage), the farmers elaborate Fentale-2 was chosen first in both places, whereas Kakaba and Adet-1 came in last (Table 8). Similar results were found by Yohannes *et al.* (2023), who found that farmers in both the Metema and Belesa experimental areas chose Fentale-2 first, while Adet-1 and Ogolicho ranked last.

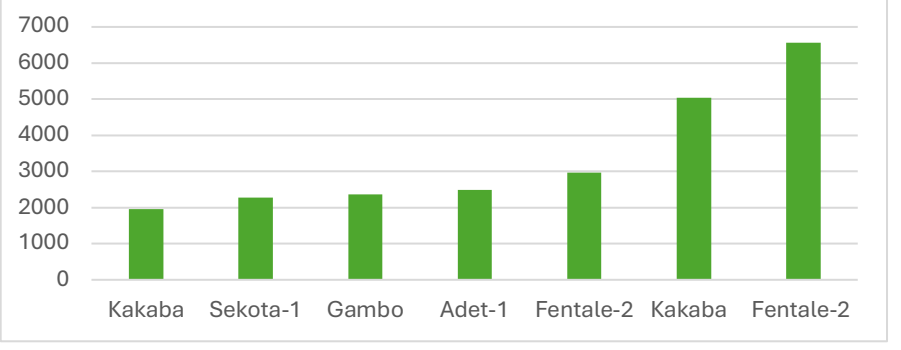

Figure 2: Grain yield (kg/ha) performance of bread wheat in irrigation season

3.3.2. Maturity date

All types had quickly attained physiological maturity, according to the combined mean. The Adet-1 variety (108 days) needed a long time to mature, whilst Kakaba (94 days) demonstrated a shorter maturation period than the other kinds. Farmers clarified that the rank of selection among varieties is determined by the maturation date; if a variety matured later, it was exposed to autumn rain, which resulted in the production of inferior seeds. The farmers placed Adet-1 lowest and Kakaba first based on the maturity date (Table 4). Due to genetic and environmental factors, wheat maturity dates varied significantly amongst genotypes even when produced during the same irrigation production season (Upadhyaya & Bhandari, 2022). Within the same variety, bread wheat grown under irrigation reaches maturity earlier than the main season. The precise maturity date and range, however, do fluctuate based on several variables, including genetic and environmental ones.

Table 4: Mean grain yield and related traits in Participatory technology evaluation program [at Sekota (Woleh) and Lalibela (Medage)]

Variety	MD	SL (cm)	TSW (g)	BM(t/ha)	GY (kg/ha)
Sekota-1	103	8.2	39	5920	2280
Adet-1	108	7.6	50.3	6560	2480
Kekeba	94	7.8	39.1	5040	1906
Fentale-2	103	10.2	54.7	7200	2960
Gambo	100	8	47.6	5280	2360
Mean	101.6	8.36	46.14	6000	2397
Max	108	10.2	54.7	7200	2960
Min	94	7.6	39	5040	1960
STDEV	5.128353	1.052616	6.950755	894.4	380.78

3.4. Qualitative data analysis

3.4.1. Farmers training / Orientation

The FREG members received training on the package, the selection criteria, and the evaluation process in both sites. Twenty-five people in the Sekota (woleh) district received technology training. Twenty female participants received training on the same subject in both the Lalibela (Medage) and Sekota areas (Table 5).

Table 5: Number of trainee stakeholders participating in the participatory technology evaluation program

Districts	FREG members		Expert		Researcher	
Sex	M	F	M	F	M	F
Sekota	13	6	2	1	2	1
Lalibela	15	9	3	0	3	1

3.4.2. Field days/visits

The Sekota Dryland Agricultural Research Center (SDARC) arranged field days and visiting programs for ARARI management and SDARC staff with farmers and stakeholders at the vegetative and physiological maturity stages of the crop, respectively. The ARARI staff visited and assessed the technology promotion study at both locations during the vegetative stage, along with some SDARC staff. At this point, the team assessed the trial's overall management rather than the varieties' performance. However, field days were arranged at both places at the physiological maturity. Model farmers, development agents (DA), woreda specialists, and researchers from other fields participated in these seminars. The participatory technology evaluation trail was visited by 87 participants, 39 from Sekota and 48 from Lalibela (Table 6).

Table 6: Field day/visiting Event participants in the participatory technology evaluation program

Districts	FREG		Das		Expert		Researcher		ARARI team		Total
Sex	M	F	M	F	M	F	M	F	M	F	M+F
Sekota	19	4	3	2	2	1	3	1	4	0	39
Lalibela	23	11	3	0	3	1	2	1	4	0	48

3.4.3. Technology evaluation and selection

The farmers in both districts used the same selection criteria, but they ranked and weighed them differently. The districts' main characteristics were earliness, spike length, tiller capacity, and vegetative performance. According to Table 7, earliness, spike length, tiller capacity, and vegetative performance rank first, second, third, and fourth at Sekota (Woleh) and second, first, third, and fourth at Lalibela (Medage). Zerga *et al.* (2018) employed a similar approach. The selection and evaluation of the varieties differ, according to the weight matrix ranking analysis; the variety with the highest value overall is ranked first, and vice versa. Except for tiller capacity, Fentale-2 was ranked highest in both districts. In both districts, Fentale-2 was chosen and ranked as the top variety by the FREGs, followed by Sekota-1 and Gambo. This result is consistent with the findings of Mihratu *et al.* (2003), who revealed that farmers primarily favored the Fntale-2 variety because of its spike length and awn features.

Table 7: Ranked criteria and weighed by farmers group at Sekota (woleh) and Lalibela (Medage) districts.

Criteria	Sekota		Lalibela	
	Weight	Rank	Weight	Rank
Earliness	1	1st	2	2nd
Spike length	2	2nd	1	1st
Tiller Capacity	3	3rd	3	3rd
Vegetative Performance	4	4th	4	4th

Table 8: summary of major farmers weighing criteria of wheat varieties and their preference rankings at Lalibela (Medage) and Sekota (Woleh) districts in 2021/2022 irrigation season.

Weighted parameter	**Score X weight**	**Varieties at Lalibela (Medage)**					**Varieties at Sekota (Woleh)**				
		Sekota-1	**Adet-1**	**Kekeba**	**Fentale-2**	**Gambo**	**Sekota-1**	**Adet-1**	**Kekeba**	**Fentale-2**	**Gambo**
Earliness	Score	3	5	1	2	4	3	5	1	2	4
	Weight	2	2	2	2	2	1	1	1	1	1
	Score X weight	6	10	2	4	8	3	5	1	2	4
Spike length	Score	2	5	4	1	3	2	4	5	1	3
	Weight	1	1	1	1	1	2	2	2	2	2
	Score X weight	2	5	4	1	3	4	8	10	2	6
Tillering Capacity	Score	1	3	4	2	5	1	2	5	3	4
	Weight	3	3	3	3	3	3	3	3	3	3
	Score X weight	3	9	12	6	15	3	6	15	9	12
Vegetative performance	Score	2	4	5	1	3	2	5	4	1	3
	Weight	4	4	4	4	4	4	4	4	4	4
	Score X weight	8	16	20	4	12	8	20	16	4	12
∑ (score x weight		**19**	**40**	**38**	**15**	**38**	**18**	**39**	**42**	**17**	**34**
Rank		**2**	**4**	**3**	**1**	**3**	**2**	**4**	**5**	**1**	**3**

4. Conclusion and Recommendations

This research showed that improved heat-tolerant wheat varieties have significant potential to increase yield under irrigation in Ethiopia's dry lowland and midland regions as well as Waglast. For most of the assessed attributes, the analysis of variance showed a significant difference between types in both sets of the experiment ($p < 0.01$). In practically every attribute, the Sora and Tay kinds outperformed the other varieties in the midland collection. The Gambo, Fentale-1, and Fentale-2 varieties performed exceptionally well in the lowland/heat-tolerant category. Fentale-2 consistently performed well in the adaptation experiment and participatory technology evaluation program in terms of yield and other significant features. Adoption scenarios can be improved and alignment with farmers' choices ensured by combining biological studies with participatory approaches. In addition to this, the farmers in both districts chose Fentale-2 over other advanced varieties in the participatory technologies' evaluation program. Together with better agronomic techniques and extension assistance, scaling up this modified variety (Fentale-2) might significantly boost wheat production and meet national food security objectives. For Abergele, Sekota, Lalibela, and comparable agroecology throughout irrigation season, the Fentale-2 variety can therefore be pre-scaled up and advised.

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Cluster Based Scaling-Up of Improved Bread Wheat Technologies: Micro-Level Evidence on Commercialization and Community Seed Multiplication in Central Ethiopia

Tesfahun Fikre* and Dirshaye Hailu

Ethiopian Institute of Agricultural Research, Wolkite Agricultural Research Center
*Corresponding author: tesfahunfikre21@gmail.com

Abstract

Smallholder agriculture remains the backbone of Ethiopia's food system, yet it suffers from low productivity and limited market engagement. In response, cluster farming and community-based seed multiplication have emerged as strategic approaches to enhance agricultural transformation and commercialization. The objective of this study was to analyze the impact of cluster-based bread wheat technology demonstration on smallholder commercialization and community seed multiplication in Sodo and Mareko Special Districts of Central Ethiopia Regional State. A convergent mixed-methods design was employed, combining a cross-sectional survey of 148 farmers (74 cluster and 74 non-cluster participants) with key informant interviews. Quantitative data were analyzed using descriptive statistics and the Mann-Whitney U test, while a Household Wheat Commercialization Index (HWCI) was used to measure market participation. Qualitative data were thematically analyzed to contextualize quantitative findings. The adoption of improved bread wheat varieties (Deka and Dursa) along with training on agronomic practice provided under the cluster intervention significantly increased yield performance, with a mean yield advantage of up to 29.4% over non-cluster farmers. Cluster participants demonstrated higher levels of input use, mechanization (100% vs 54%), and market participation with 55% reaching higher compared to 41.4% of non-cluster farmers. The study confirmed that cluster-based wheat farming coupled with community seed multiplication enhances smallholder bread wheat commercialization and supports local seed system. Strengthening local innovation platforms, improving mechanization access, and institutionalizing seed quality control at grassroots levels are crucial for sustainability.

Keywords: Economies of scale, farming, innovation, yield, transformation

1. Introduction

Agriculture plays a pivotal role in Ethiopia's economy, contributing 32% to the national GDP, generating more than 75% of export earnings, and employing over 60% of the country's population (NBE, 2023). Beyond its economic importance, the sector remains central to national food security, rural employment, and household livelihoods (CSA, 2020; ATA, 2019; Spielman *et al.*, 2011). Despite this significance, Ethiopian agriculture is dominated by smallholder farmers which faces persistent challenges of low productivity, limited market engagement, and structural bottlenecks such as fragmented landholdings, weak input systems, and poor market linkages (Haile *et al.*, 2022; Gebremedhin & Melesse, 2018). As a result, cereal yields often remain below global averages, reflecting the need for transformative approaches to strengthen productivity and commercialization (World Bank, 2020).

In response to these constraints, cluster farming has emerged as one of the key strategies to accelerate smallholder commercialization and agricultural transformation. Cluster farming involves organizing smallholder farmers into geographically proximate groups who grow the

same crop using harmonized agronomic practices and inputs (ATA, 2018). Within Ethiopia, this model is integral to the Agricultural Commercialization Cluster (ACC) initiative and supports crop-specific production intensification, market coordination, and improved extension delivery. Agricultural commercialization, in this context, goes beyond the sale of output—it reflects a production system where farmers make decisions on crop choice and input use with the goal of maximizing profit (Pingali & Rosegrant, 1995). Smallholder participation in cluster farming thus reflects a deliberate shift toward improved input use, surplus production, and efficiency gains (Endalew *et al.*, 2024). Within the Ethiopian Institute of Agricultural Research (EIAR) technology transfer pathway, cluster farming serves as the platform for large-scale demonstrations following technology generation and pre-extension testing.

Community-based seed multiplication complements cluster farming by addressing the chronic shortage of quality seed in Ethiopia, where the formal sector supplies less than 25% of national demand (FAO, 2015; Bishaw *et al*., 2012). Local seed multiplication improves farmers' access to improved varieties, accelerates technology diffusion, and strengthens resilience (McGuire & Sperling, 2016). Integrated with cluster production, it supports wider adoption of improved varieties and enhances seed system functionality. This study draws on the Agricultural Innovation Systems (AIS) framework, which emphasizes multi-actor collaboration and institutional learning (Klerkx *et al.*, 2012; World Bank, 2006), and the concept of economies of scale, which explains the cost-efficiency gains from coordinated production (Dorward, 2009). Together, these perspectives help explain how cluster-based interventions enhance productivity, seed access, and commercialization.

In technology pre-scaling initiative, farmers in Sodo and Mareko Special Districts were mobilized to jointly cultivate improved bread wheat varieties (Daka and Dursa) on contiguous plots while receiving coordinated training and market linkage support. Non-cluster farmers did not receive the full intervention package. Therefore, yield and commercialization gains observed in cluster areas reflect the combined effect of integrated technology delivery, collective production, and seed system strengthening. The objective of this study is to assess the contribution of cluster-based bread wheat technology demonstration to household-level wheat commercialization and community-based seed multiplication in the study area.

Theoretical framework

This study applies two complementary theoretical perspectives Agricultural Innovation Systems (AIS) and Economies of Scale to explain the mechanisms through which cluster farming influenced technology uptake, productivity, and commercialization in Sodo and Mareko Special Districts. The AIS framework emphasizes the importance of multi-actor collaboration, institutional learning, and knowledge exchange in driving agricultural innovation (Klerkx *et al.*, 2012; Hall *et al.*, 2001). In this study, cluster farming functioned as a localized innovation platform where farmers, researchers, and extension agents collectively tested and refined improved bread wheat varieties. This interactive learning environment enhanced technical support, reinforced farmer capacity, and accelerated the diffusion of improved practices across participating communities.

The Economies of Scale theory explains how organizing farmers into coordinated production units reduces transaction and production costs, facilitates bulk input acquisition, enables shared use of machinery, and strengthens collective marketing (Dorward, 2009; Barrett *et al.*, 2010). These coordinated efficiencies improve farmers' competitiveness, increase bargaining power, and support deeper participation in grain and seed markets. Together, AIS and Economies of Scale provide a robust theoretical lens for understanding how cluster farming enhances smallholder commercialization while strengthening community-based seed multiplication systems.

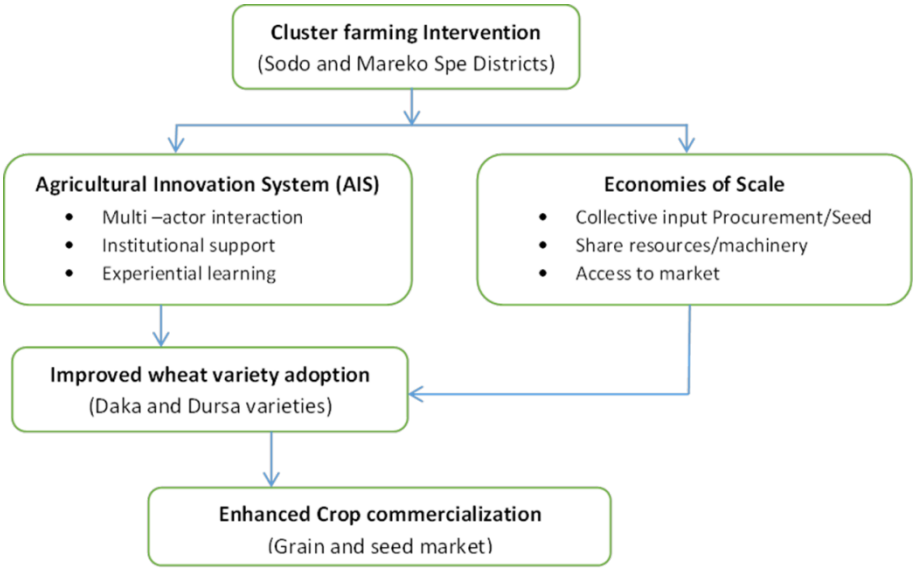

Figure 1. Theoretical framework of the study

2. Materials and Methods

2.1. Description of the study area

Sodo District, in the Misrak Gurage Zone of Central Ethiopia Regional State, is situated between 8°09'–8°45' N latitude and 38°37'–38°71' E longitude. It is identified by the Ethiopian Agricultural Transformation Institute as a high-potential area for wheat production and commercialization. The district is predominantly mid-altitude, with elevations ranging from 1,800 to 3,040 meters above sea level. Major crops grown include wheat, teff, beans, and maize, alongside livestock rearing as a key livelihood activity. Sodo is bordered by Debub Sodo, Mareko Special District, and the Oromia Region. Mareko Special District, located northeast of Sodo, has similar agro-ecological conditions, with altitudes between 1,800 and 2,076 meters and a comparable bimodal rainfall pattern. Its agricultural focus includes wheat, maize, beans, and hot pepper. Both districts face development challenges such as soil erosion, low agricultural productivity, and poor access to clean water, healthcare, and education. This study was conducted in six rural kebeles across the two districts, selected for their significant bread wheat cultivation.

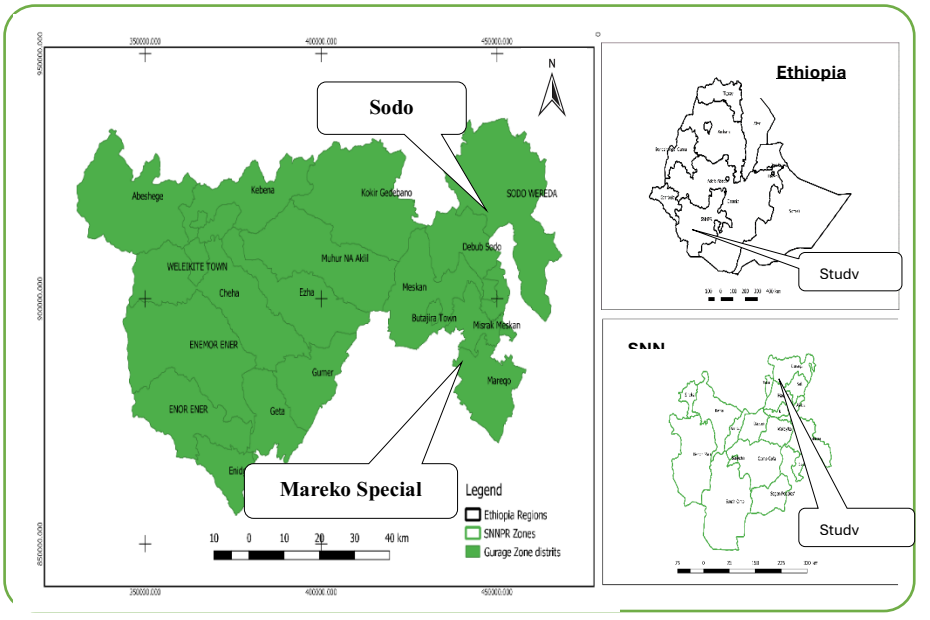

Figure 2. Map of the study areas; Source: CSA, 2015

2.2 Sampling techniques and methods of data collection

The study employed a convergent mixed methods approach to comprehensively assess the impact of cluster farming on smallholder commercialization and community seed multiplication. By integrating both quantitative and qualitative data collected concurrently, the study aimed to provide a holistic understanding of how cluster-based interventions influenced input use, market participation, and seed system development among participating and non-participating farmers (Creswell & Plano Clark, 2017). This approach was particularly valuable for triangulating findings, enriching interpretation, and enhancing the robustness of the analysis (Tashakkori & Teddlie, 2010). A community-based comparative cross-sectional survey was conducted to capture micro-level differences in wheat production practices, productivity, and commercialization outcomes between cluster and non-cluster farmers (Bryman, 2016).

2.2.1. Sampling method

The study employed a multi-stage purposive sampling method to select representative participant farmers. Farmers who were members of the cluster farming initiative were selected as the treatment group. In the same kebeles, farmers who did not participate in cluster farming or any other cluster production initiatives were purposively selected as non-cluster (control) farmers, enabling a comparative analysis. From the rural kebeles of Sodo and Mareko Special Districts, Wudiget and Wudasa kebeles were purposively chosen based on their active involvement in the cluster farming intervention and their potential for community seed multiplication. A stratified sampling technique was then used to ensure representation of various household types, landholding sizes, and participation levels. Farmer lists were obtained from local agricultural offices and development agents, and random sampling was applied within each kebele to select households. The total sample size was 148 farmers, with 74 farmers from the cluster farming group and 74 from the non-cluster group. This design enabled the study to examine differences in commercialization

levels, input use, and seed production outcomes between the two groups under comparable agro-ecological and institutional conditions.

2.2.2 Data collection method

The quantitative component of the study involved a community-based cross-sectional survey designed to assess the level of smallholder commercialization and input utilization among cluster farming participants and non-participants. A structured interview schedule was administered through face-to-face interviews, capturing key variables such as seed type, fertilizer use, access to mechanization, yield levels, and market engagement. To complement the survey findings, qualitative data were collected through key informant interviews with farmers, extension workers, and local seed union representatives. These discussions aimed to explore participant perceptions and experiences related to the cluster farming intervention, including technology adoption, input access, and seed marketing dynamics. The qualitative insights provided valuable context for interpreting the survey results and deepened the understanding of how collective action influenced smallholder commercialization and community-based seed multiplication in the study area.

2.3. On-farm technology promotion

The implementation of the cluster-based bread wheat technology scaling-up began with the purposeful selection of demonstration sites and host farmers in close collaboration with the Sodo District and Mareko Special District Agricultural Offices. The selection criteria emphasized farmers' willingness to engage in demonstrations and the accessibility of their farmlands for continuous supervision and learning. To initiate coordinated implementation, a consultative meeting was held in Butajira city to establish a functional innovation platform aimed at aligning key stakeholders around the intervention's goals. Participants included development agents from selected kebeles, officials from the district agriculture office, Ediget Farmers Union, cluster farmers, seed producer cooperatives, the Wolkite Seed Quality Regulatory Office, and researchers from Wolkite Agricultural Research Center. During the meeting, each actor clearly defined their roles and responsibilities, fostering a sense of ownership, collaboration, and accountability to ensure the success of the initiative.

Capacity building was a key element of the intervention, with 74 farmers, 10 agricultural experts, and 20 development agents receiving practical training from Wolkite Agricultural Research Center (WkARC). To support the intervention, WkARC supplied 4.5 tons of “Deka” and 2.5 tons of “Dursa” bread wheat basic seeds to farmers in Sodo and Mareko Special Districts, respectively, on a revolving seed basis to promote adoption and sustainability. Regular field monitoring was carried out by a joint team from WkARC, the Wolkite Seed Quality Regulatory Office, and the Sodo District Agriculture Office to assess performance and ensure seed quality. Demonstrations were conducted over two cropping seasons on 24 selected farmers’ fields, each treated as a replication. Plots measured 200 m^2, with two farmers from each farmer association participating, collectively covering 30 hectares as a single production cluster. Recommended agronomic practices such as 20–25 cm row spacing, 150 kg/ha seed and NPS fertilizer application, and manual weeding were applied. A farmers’ field day was organized to promote learning and collaboration, enabling farmers, researchers, extension workers, and cooperative leaders to evaluate the improved bread wheat variety and provide feedback on the intervention.

Table 1: Description of the demonstrated bread wheat varieties

Varieties' name	Year of release	Altitude (masl)	Rainfall (mm)	Grain yield (t/ha)	
				Research field	Farmers field
Deka	2018	1600-2100	500-800	3.1-5.6	2.8-
Dursa	2020	1600-2100	500-800	5.1-6.2	4.2-6.1

5. Data analysis method

The collected quantitative data were first checked for completeness and consistency, then entered into SPSS version 20 for analysis. Descriptive statistics such as means, standard deviations, frequencies, and percentages were used to summarize key socio-economic characteristics, input use patterns, and commercialization indicators of cluster and non-cluster farmers. To compare differences in commercialization levels, input utilization, and yield outcomes between the two groups, non-parametric inferential statistics, particularly the Mann-Whitney U test, were employed due to the small sample size and non-normal distribution of some variables. Agricultural commercialization in this context is understood as the extent to which farmers make production and input use decisions based on profit maximization principles (Pingali and Rosegrant, 1995). In this study, a household wheat commercialization index (HWCI) was used to explore how levels of commercialization differ between farmers participated in the cluster and otherwise.

$$HWCI = \frac{Gross\ value\ of\ bread\ wheat\ sale}{Gross\ value\ of\ bread\ wheat\ production}\ x\ 100$$

The index enabled the classification of farmers into five distinct commercialization categories: households with a HWCI value of 0 were categorized as subsistence producers. Those with values less than 25% were classified as low-commercialized; 25–50% as medium-commercialized; 50–75% as high-commercialized; and above 75% as very high-commercialized. This categorization provided a basis for comparing the commercialization levels between cluster-participating farmers and non-participants. The qualitative data collected through Key Informant Interviews (KIIs) were thematically analyzed. Themes were developed around farmers' experiences with cluster farming, adoption of the improved wheat variety, access to inputs, and engagement in seed multiplication and marketing. These qualitative insights were used to enrich and triangulate the quantitative findings, offering a more nuanced understanding of the intervention's impact on smallholder commercialization and seed system strengthening.

Furthermore, the grain yield data from both cluster participants and non-participants underwent analysis to evaluate the technological gap, technological index, and yield advantage, following the methodology outlined by (Samui *et al.*, 2000).

Technology gap = Potential yield- Demonstration yield

$$\text{Technological index (\%)} = \frac{\boldsymbol{Potential\ yield} - \text{Demonstration } \boldsymbol{yield}}{\boldsymbol{Potential\ yield}}$$

$$\text{Yield advantage (\%)} = \frac{\boldsymbol{yield\ of\ new\ variety - yield\ of\ local\ (standard)check}}{\boldsymbol{yield\ of\ local\ (standard)\ check}}\ \text{X } 100$$

3. Results and Discussion

3.1. Technology adoption and innovation uptake: AIS Perspective

High mean yields and significant yield advantage of the improved bread wheat varieties Deka and Dursa can be attributed to the coordinated support system established through the cluster farming intervention. Specifically, Deka **demonstrated** a yield advantage of 29.4% over the variety grown by non-cluster farmers i.e. Kakaba in the same kebele**,** while Dursa showed a 21.15% advantage**.** These gains resulted from the integrated efforts of farmers, researchers, development agents, and seed regulatory authorities within the Agricultural Innovation System (AIS).

Table 3**.** Analysis of bread wheat varieties in the study areas (N=74)

Year	Districts	Variety name	Grain yield(t/ha)	Mean yield advantage (%)	Mean Technology gap (t/ha)	Technology gap index (%)
			Mean ± SD			
2021/22	Sodo	Deka	4.40 ± 0.31	26.8	0.05	1.15
	Mareko Special District	Dursa	3.95± 0.11	16.2	1.20	23.3
2022/23	Sodo	Deka	4.49±0.35	29.4	-0.14	-3.22
	Mareko special district	Dursa	4.06 ± 0.13	21.15	1.09	21.2

Source: (Own computation, 2023)

The cluster approach facilitated joint demonstration plots, farmer training on good agronomic practices, and timely input supply, all of which fostered an enabling environment for innovation uptake. The delivery of technical support and post-harvest guidance by extension agents further enhanced productivity and encouraged behavioral change in crop management practices. This reflects a core principle of the AIS framework, which highlights collaborative learning, adaptive research, and institutional coordination as critical drivers of technology adoption (Klerkx *et al.*, 2012; World Bank, 2006; Hall *et al.*, 2001;). Importantly, the comparison for the reported yield advantages is based on data collected from non-cluster farmers who cultivated local or previously adopted improved varieties without access to cluster-level training, improved inputs, or coordinated support**.** This control group served as the baseline for calculating the yield gains attributable to the cluster-based intervention.

3.2. Cost efficiency and market participation: economies of scale perspective

Table 4. Degree of commercialization in wheat output market participation

Total yield supplied to market by farmers	Cluster participant (%)	Non-cluster participant (%)	Level of commercialization	χ2
HWCI=0	-	-	Subsistence	0.027*
HWCI>25%	14.7	25.6	Low	
HWCI 25-50%	30.5	33	Medium	
HWCI 50-75%	29.9	25	High	
HWCI <75%	24.9	16.4	Very high	

Source: (Own computation, 2023)

Cluster-based organization enabled farmers to access improved inputs such as seed and agro-chemicals collectively, and to utilize mechanization services efficiently, 100% mechanization use among cluster farmers versus 54% for non-cluster participants. This reduced per-unit production costs and enhanced productivity, consistent with the Economies of Scale theory**,** which posits that scaling up production activities leads to cost efficiencies and improved competitiveness (Pingali, 2012; Dorward, 2009).

Moreover, the commercialization data indicate that 55% of cluster participants achieved high or very high levels of wheat market participation**,** compared to 41.4% of non-cluster farmers**.** This finding aligns with prior studies that emphasize the role of farmer organization and coordinated input-output linkages in enhancing market orientation. For instance, **m**arket participation among Ethiopian smallholders increased significantly when farmers were engaged in collective marketing and received institutional support(Gebremedhin and Jaleta (2012). Similarly, It was reported that wheat farmers involved in the Agricultural Growth Program (AGP) exhibited higher commercialization levels due to improved access to extension, inputs, and market information (Melesse, 2018). The ability to sell directly to Ediget Union at premium prices underscores enhanced bargaining power and reduced transaction costs, key features emphasized in economies of scale literature (Shiferaw *et al.*, 2011; Barrett *et al.*, 2010).

3.3. Social capital, learning, and mutual support

Farmers' witnesses revealed that the cluster farming approach fostered a culture of mutual support, accountability, and experiential learning all of which are essential mechanisms within innovation systems. The establishment of group rules and collective labor sharing during critical tasks like weeding not only improved efficiency but also enhanced resilience and trust among members. This dynamic mirrors findings from AIS literature which underscore the importance of social capital in enabling sustained innovation (Merenehi *et al.*, 2023; Röling, 1992).

I believe that working in a cluster has created a sense of positive competition and collaboration among us. I have noticed formerly reluctant farmers had visited frequently and well managed their farm by seeing others. We have established rules and regulations abiding with punishment, if not tracked, on crop management including weeding, agrochemical application and timely harvesting.

Farmer Mesfin Anbese (Soloke cluster Coordinator)

Technical support given from researchers as well as experts of kebele and woreda was valuable for us. The kebele Development Agents (DAs) told us earlier that unless we are stricter on producing quality seed, the Seed enterprise and unions will not receive it. Accepting the advice provided, we had careful management starting from the farm to its post-harvest phase. In terms of cooperation, even if we had a culture of cooperation in the past; this cluster farming provided us a more opportunity to support each other. For instance, I had back pain during the weeding time and all members of the cluster have helped me with it.

Farmer Mande Abera (Soloke cluster)

According to Farmer Mande Abera, who is quoted above, the technologies especially improved seed of bread wheat and the advisory services were appreciated, and the LSD approach made the competitors at the same time co-operators.

3.4. Seed system development and institutional integration

The integration of 86.9 tons of Certified-1 seed into the formal system over two seasons demonstrates how cluster farming bridged informal and formal seed systems. By meeting quality standards and ensuring traceability, cluster farmers not only addressed local seed demand but also contributed to national seed supply strategies. This outcome exemplifies how coordinated innovation platforms can serve both productivity and institutional development goals, as posited by AIS theory (Lundvall, 2010).

Table 6. Clusters contribution for the formal seed system

Cropping season	Name of the district	Variety	Area coverage (ha)	Seed Class	Seed Supplied (tons)	Seed receiver
2021/22	Sodo	Deka	5	Certified-1	10.3	
	Mareko Special	Dursa	7	Certified-1	7.6	Eidget Union
2022/23	Sodo	Deka	30	Certified-1	56	Eidget Union
	Mareko Special	Dursa	20	Certified-1	13	South Seed Enterprise

Source: (Own computation, 2023)

Figure 4. The clusters field performance and farmer field day events

4. Conclusion and Recommendations

This study demonstrated that the cluster-based wheat farming approach, when implemented as a comprehensive package combining improved seed varieties, agronomic training, extension support, and market linkages substantially enhanced productivity, commercialization, and seed system development in Central Ethiopia. The scaling up of Daka and Dursa varieties within clusters resulted in significant yield advantages of 28% and 18.6% or 29.4% and 21.15% based on site-specific results compared with non-cluster farmers. Cluster participants also exhibited higher levels of mechanization, lower production costs, and stronger market participation with 55% achieving high to very high commercialization compared with 41.4% among non-cluster farmers. Socially, the approach strengthened collaboration, trust, and experiential learning among farmers, while enabling the production and formal supply of more than 86 tons of quality seed an important contribution to local seed systems and technology diffusion.

Based on these findings, the cluster farming model should be promoted and scaled up as a holistic agricultural development strategy, rather than viewed merely as a land-merging practice. Future interventions should prioritize bundling inputs, training, extension support, and market access to maximize the benefits of clustering. Strengthening extension services, expanding access to mechanization, and promoting farmer-to-farmer learning and community-level coordination are essential to sustain the productivity and commercialization gains achieved through cluster farming.

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Evaluation of Introduced Hybrid Tomato (Lycopersicon esculentum L. Mill) Varieties in the Central Rift Valley of Ethiopia

Yirssaw Demeke Ambaw* and Tarekegn Yoseph Samago

School of Plant and Horticultural Sciences, College of Agriculture, Hawassa University
*Corresponding author: yirssawdemeke@hu.edu.et

Abstract

Tomato (Lycopersicon esculentum L. Mill) serves as a crucial cash crop in Ethiopia, yet its production faces significant constraints from environmental stressors, limited access to improved cultivars and other agronomic managements. Addressing these challenges requires climate-smart agricultural solutions, particularly through the introduction of high-performing varieties. This study assessed the agronomic performance of two hybrid tomato cultivars (PO364 and PO380) at six environments (Meki I, Meki II, Adami Tullu, Wondogenet, Dori and Hawassa) under irrigated conditions in Ethiopia's central rift valley during the 2023/2024 dry season (October-January). The varieties were arranged in a Randomized Complete Block Design (RCBD) with three replications at six environments. The result indicated that there were significant ($P \leq 0.001$) varietal differences for all parameters measured. Both hybrids demonstrated exceptional agronomic performance, featuring high fruit set rates (87-97%), early maturation (60-96 days), superior marketable yields (95-99 t/ha), total yields exceeding 100 t/ha (103-106 t/ha). The cultivars also exhibited premium quality attributes, including excellent fruit firmness (85-87 N) and optimal total soluble solids content (3.9-4.3 °Brix). Their consistent performance across multiple trial locations indicates strong potential for adoption in similar agro-ecological zones. However, further investigation of their pest and disease resistance profiles across Ethiopia's diverse growing regions is recommended to confirm their nationwide suitability. These findings position PO364 and PO380 as promising candidates for enhancing tomato productivity and climate resilience in water-limited production systems.

Keywords: Adaptability, fruit quality, shelf life, yield

1. Introduction

Tomato (*Lycopersicon esculentum* L. Mill) is an important cash-generating commodity for the fresh and processing markets worldwide (FAO, 2023). In Ethiopia, tomato is largely produced in areas with an altitudinal range from 700 to 2200 meters above sea level (m.a.s.l.) and significantly contributes to the economic and social welfare of millions of Ethiopians (Abebe & Tola, 2022). However, its production in the country has been restricted to certain areas, and the productivity remains very low, averaging 8 t/ha compared to the global average yield of 38 t/ha (FAOSTAT, 2023). According to recent reports, the low yield of the crop is attributed to factors such as a shortage of improved and adapted varieties, disease and insect pest pressures, high post-harvest losses, climate change, and limited awareness of climate-smart agriculture (CSA) technologies (Tesfaye *et al*., 2021).

To address these challenges, developing, adopting, and promoting CSA-compliant tomato yield-boosting technologies is crucial for sustainably improving smallholder farmers' incomes and livelihoods. One promising approach is the introduction and evaluation of tomato varieties released in other regions for their adaptability and yield performance

under Ethiopian conditions. In line with this, over 20 commercial hybrid tomato varieties have been verified and are under production in Ethiopia (MoA, 2022). However, due to the rapidly growing demand for tomatoes driven by local consumption, agro-industrial needs, and export markets, the existing hybrid varieties cannot fully meet the country's requirements. Continuous introduction and participatory evaluation of newly released hybrids with farmers could help bridge this supply gap. Therefore, this study was designed to assess the adaptability and yield performance of two introduced hybrid tomato varieties (PO364 and PO380) in the Central Rift Valley of Ethiopia under supplemental irrigation.

2. Materials and Methods

2.1. Study sites

The evaluation trial was conducted in six representative tomato-growing sites in Ethiopia during the 2022/2023 off-season under supplementary irrigation. Three sites were selected from Oromia Region: Shubigemo (Meki I) and Bekelagrissa Kebeles (Meki II) (Meki district), Abossa Kebele (Adami Tullu district). The other three testing sites were selected from Sidama Region: Sama Kebele (Dore Bafeno district), Wendo Genet Agricultural Research Center, and Hawassa University Research Center. To ensure optimal growing conditions supplementary irrigations were applied in all testing sites.

2.2. Experimental Design and Treatment

The study evaluated two new hybrid varieties (PO364 and PO380) sourced from the Community Plant Variety Office, Italy, along with a check variety, Gelilea from Israel. The treatments (three tomato varieties) were arranged in Randomized Complete Block Design (RCBD) with three replications at each testing site. The gross plot size used for the experiment was 5m × 20m each at each testing site. Tomato seeds were raised on planting trays in the nursery following standard protocols for seedling production and management, including controlled fertilization, integrated pest management and optimal growing conditions. The seedlings were planted with a planting density of 40,000 plants/ha (0.5m intra-row × 1.0m inter-row spacing). Uniform agronomic practices across all sites were employed based on the national recommendations (100kg/ha NSP during transplanting and 200kg/ha urea in two equal splits i.e 100kg/ha at the time of transplanting and the remaining 100kg/ha as side-dressed three weeks after transplanting). Harvesting was done when the tomatoes were ripe or nearly ripe, and quality assessments were performed.

2.3. Data collections and analysis

Data were collected on growth traits, yield and yield components, postharvest quality attributes and farmers preference for the evaluated varieties of tomato. At physiological maturity, growth, yield and yield components, and fruit quality data were collected from five randomly selected tomato plants in the middle five rows of each variety per plot. The growth traits considered include vine length (cm), number of branches per plant, days to 50% flowering, days to first harvest, and days to last harvest. Traits related to yield and yield components include number of clusters per plant, flowers per cluster, fruits per cluster, fruit set percentage (%), average fruit weight (g), fruit dimensions (length and width, cm), marketable and unmarketable yield (t/ha), and total fruit yield (t/ha). Postharvest quality attributes include fruit firmness (N), total soluble solids (TSS) (°Brix), titratable acidity (%),

and weight loss (%). Postharvest quality evaluations were performed at Hawassa University's School of Food Science, Nutrition, and Postharvest Technology laboratory. Farmers who participated in the trial were asked to rank their preferred tomato variety based on specific criteria using a pair-wise ranking method (1 for being worse, 2 for fair and 3 for best) as stated in Russell (1997). The scores were averaged and used to determine the performance of each variety at each site. Since homogeneity of variance was heterogenous, the collected data was subjected to a location-specific Analysis of Variance (ANOVA) using R statistical software (R Core Team, 2023). Treatment means were separated using Fisher's Least Significant Difference (LSD) test at $p \leq 0.05$ (Montgomery, 2005).

3. Results and Discussion

The results of the study are presented based on location specific due to heterogeneity of variance and the key finding of the results are summarized for the six testing sites separately.

3.1. Growth, yield and yield component and postharvest quality

Meki-I Site: The data analysis result indicated that PO364 exhibited the tallest vine length (88.4 cm) compared to the check variety (89 cm), the highest number of branches (8.4), clusters per plant (16.1), and flower per cluster (6.3). It also showed the earliest flowering (32.0 days), highest fruit set percentage (95.2%), the earliest (60 days) and latest (94 days) maturity dates compared to other varieties. Additionally, PO364 produced the highest fruit weight (176.2g), marketable yield (98 t/ha) and total fruit yield (104 t/ha), the highest fruit firmness (85.4N) and total soluble solids (TSS) of 4 ^{o}Brix compared to the others (Table 1).

Meki-II Site: The result showed PO364 had the tallest vine length (89.6 cm), highest number of branches (8.6) and clusters per plant (16.8) at this site. It also showed the earliest flowering (33 days), highest fruit set percentage (96.9%), the highest fruit weight (176g), marketable yield (99 t/ha), total fruit yield (105.5 t/ha). Moreover, PO364 exhibited the highest fruit firmness (85.8N) and TSS of 3.9 ^{o}Brix (Table 1).

Adame Tulu Site: The result indicated that Gelilea and PO380 had statistically similar vine lengths (87.6 cm). Notably, PO364 had the highest number of branches (8.2), clusters per plant (15.9), and flower per cluster (6.2). It showed the earliest flowering (34 days), highest fruit set percentage (95.2%), the highest fruit weight (175.8g), marketable fruit yield (95 t/ha) and total fruit yield (103 t/ha). Furthermore, PO364 exhibited the highest fruit firmness (85.2N) and TSS of 4.1 ^{o}Brix compared to the others (Table 1).

Wondo Genet Site: The result showed that tomato variety PO364 was the tallest (91 cm) and had the highest number of branches (8.8), clusters per plant (17), the earliest flowering (36 days) and highest fruit set percentage (97%). It has the highest fruit weight (176.9g), marketable fruit yield (95.5 t/ha), total fruit yield (106 t/ha), the highest fruit firmness (86.8N) and TSS of 4.3 ^{o}Brix compared to the others (Table 1).

Dori Bafano Site: Similarly, tomato variety PO364 showed the tallest (90.6 cm) vine length and had the highest number of branches (8.4) and clusters per plant (16.8). Again, PO364 showed the earliest flowering (35 days), highest fruit set percentage (96.9%), the highest

fruit weight (176.4g), marketable fruit yield (98 t/ha), total fruit yield (105 t/ha), the highest fruit firmness (86.4N) and TSS of 4.2 °Brix compared to the others (Table 1).

Hawassa Site: Tomato variety PO364 had the tallest vine length (90.8 cm), the highest number of branches (8.6), clusters per plant (17.2), and flower per cluster (6.6) compared to the check variety (89 cm). Additionally, it also showed the earliest flowering (34 days), highest fruit set percentage (97%), the earliest (62 days) and latest (79 days) ripening dates for fruits (Table 1). Conversely, the check variety had the lowest number of branches (6.4), clusters per plant (13.7), and flower per cluster (5.1). Furthermore, the check and PO380 took 73-78 days and 70-75 days, respectively, to produce the first and last ripened fruits. PO364 had the highest fruit weight (176.1g), marketable fruit yield (90.5 t/ha), total fruit yield (104.5 t/ha), the highest fruit firmness (86.2N) and TSS of 4.1 °Brix. The check variety had the lowest fruit length (7 cm), fruit diameter (5.6 cm), marketable yield (9.3 t/ha), and the highest unmarketable yield (9.2 t/ha). PO380 showed the lowest fruit weight (162.9g), total yield (18.4 t/ha), fruit firmness (75.4N), the lowest TSS (3.1 °Brix) and the highest weight loss (24%) (Annex Figure 1, 2, and 3).

Table 1: Mean values of tomato growth parameters, yield and yield component and postharvest quality at each testing site

Location	Variety	VL (cm)	NBPP (No)	NCPP (No)	DTF (days)	NFlPC (No)	NFrPC (No)	FrS (%)	DFH (days)	DLH (days)
Meki-I	Gelilea	89	6	13.1	40	4.8	4.3	89.6	72	90
	PO364	88.4	8.4	16.1	32	6.3	6	95.2	60	94
	PO380	87.8	6.6	15.2	34	5.5	5	90.9	67	75
Meki-II	Gelilea	88.8	6.2	13.3	42	5	4.4	88	72	90
	PO364	89.6	8.6	16.8	33	6.4	6.2	96.9	61	94
	PO380	88.2	6.8	15.6	34	5.6	5.1	91.1	67	75
A/Tulu	Gelilea	87.6	5.8	13	41	4.8	4.2	87.5	73	89
	PO364	88.6	8.2	15.9	34	6.2	5.9	95.2	60	95
	PO380	87.6	6.4	15.4	35	5.4	4.9	90.7	69	76
W/Genet	Gelilea	90	6.8	13.6	45	5.4	4.8	88.9	75	93
	PO364	91	8.8	17	36	6.6	6.4	97	65	98
	PO380	90.4	7.4	15.6	37	5.8	5.2	89.8	70	78
Dori	Gelilea	90.2	6.6	13.4	43	5.3	4.7	88.7	74	90
	PO364	90.6	8.4	16.8	35	6.4	6.2	96.9	63	96
	PO380	90.4	7.6	15.2	36	5.6	5.1	91.1	69	76
Hawassa	Gelilea	89	6.4	13.7	40	5.1	4.6	90.2	73	78
	PO364	90.8	8.6	17.2	34	6.6	6.4	97	62	79
	PO380	89.6	7.4	15.8	35	5.9	5.4	91.5	70	75
F-value		12.95	51.77	107.24	70	81.53	158.69	46.22	91.36	15.53
Pr > F		0.0003	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
LSD		0.5973	0.2766	0.2769	0.9096	0.1322	0.1174	0.9807	1.0416	4.2515
CV (%)		0.52	2.95	1.42	1.91	1.8	1.73	0.83	1.19	3.86

Table 1 continued…….

Location	Variety	FL (cm)	FD (cm)	FW (g)	MY (t/ha)	UMY (t/ha)	Y (t/ha)	FF (N)	TSS (°Brix)	TA (%)	WL (%)
Meki-I	Gelilea	6.9	5.4	163	72.5	16.5	89	82.8	3.3	7	15
	PO364	8.4	6.2	176.2	98	6	104	85.4	4	6	12
	PO380	8.6	6.6	162.7	83	7	90	74.2	2.9	5.5	20
Meki-II	Gelilea	7	5.4	163.4	66	24	90	82.6	3.2	6.8	16
	PO364	8.2	6.4	176	99	6.5	105.5	85.8	3.9	5.8	11
	PO380	8.4	6.6	163	82.5	8	90.5	74.6	3	5.3	21
A/Tulu	Gelilea	6.8	5.2	162.9	72.5	15.5	88	82.4	3	6.5	15
	PO364	8	6	175.8	95	8	103	85.2	4.1	5.9	12
	PO380	8.2	6.4	162.5	83	6	89	74.1	2.8	5.4	23
W/Genet	Gelilea	7.2	6	164.2	64	28	92	83.8	3.4	6.2	12
	PO364	8.4	6.8	176.9	95.5	10.5	106	86.8	4.3	5.2	10
	PO380	8.8	6.8	163.9	79.5	11.5	91	75.6	3	4.6	18
Dori	Gelilea	7.1	5.8	163.8	71	20	91	83.2	3.1	6.7	13
	PO364	8.2	6.6	176.4	98	7	105	86.4	4.2	5.6	12
	PO380	8.6	6.6	163.1	82	8	90	75.4	2.9	4.8	20
Hawassa	Gelilea	7	5.6	163.6	46.5	46	92.5	82.2	3.2	6.4	16
	PO364	8.4	6.8	176.1	90.5	14	104.5	86.2	4.1	5.4	13
	PO380	8.6	6.8	162.9	75	17	92	75.4	3.1	4.9	24
F-value		150.4	38.01	4169.6	54.55	19.82	41.86	521.7	49.62	64.87	44.45
Pr > F		0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
LSD		0.111	0.174	0.196	0.902	0.999	0.582	0.424	0.147	0.175	1.279
CV (%)		1.13	2.17	0.09	3.09	24.41	1.75	0.41	3.34	2.36	6.32

Where: VL- vine length, NBPP-No of branch/plant, NCPP-No of cluster/ plant, DTF-Days to 50% flowering, flowering, NFlPC-No of flowers/cluster, NFrPC-No of fruits/cluster, FrS-Fruit set, DFH-Days to first Harvest, DLH-Days to last harvest, FL-Fruit length, FD-Fruit diameter, FW-Fruit weight, MY-Marketable Yield, UMY-Unmarketable yield, Y-Yield, FF-Fruit firmness, TSS-Total soluble solid, TA-Titratable acidity, WL-Weight loss, LSD-Least significance difference test, CV-Coefficient of variation

The overall analysis of growth, yield, yield components and postharvest quality analysis indicated that there was variation among the tested tomato varieties across the locations. Overall, the result indicated that hybrid tomato variety PO364 performed better than the other two tested varieties in all locations except at Adami Tulu site. Key morphological and phenological traits including vine length, branching pattern, cluster and flower production, fruit set efficiency, and days to maturity, serve as critical indicators for evaluating tomato varietal performance and yield potential (Pandey, 2006; Shushay *et al*., 2013). In this study, the tested varieties showed similar vine length with the report of Meseret *et al*. (2012). Similarly, other growth and yield parameters (branches per plant, clusters per plant, flowers/fruits per cluster, and fruit set percentage) aligned with findings from earlier studies (Fayaz *et al*., 2007), underscoring the genetic stability of these traits across diverse growing conditions.

Fruit dimensions (length, diameter) and weight are pivotal for market acceptability and yield estimation. PO364 outperformed other varieties, with fruit length (8–8.8 cm) and width (6–6.8 cm) exceeding values reported by Kaushik *et al*. (2011). Its superior fruit weight (175.8–176 g) further confirmed its genetic advantage, falling within the standard range (162.5–176 g) documented by Lemma (2002). These results reinforce that fruit morphology is predominantly genotype-dependent (Atherton & Rudich, 1986), emphasizing the need for targeted varietal selection.

Marketable yield, a direct determinant of profitability, was highest in PO364 (19–19.8 t/ha), comparable to the 7.21–43.80 t/ha range observed by Meseret *et al*. (2012). Conversely, unmarketable yields—driven by abiotic (sunburn, cracking) and biotic (diseases, pests) stressors—were minimized in PO364 and PO380 (1.2–2.8 t/ha) relative to the check variety (3.1–9.2 t/ha). This disparity may reflect varietal differences in pericarp thickness, a known factor in fruit resilience (Capuno *et al*., 2007). Field challenges (e.g., late blight, *Tuta absoluta*) further exacerbated losses, highlighting the need for integrated pest management in tomato production.

Postharvest Quality Attributes such as fresh-market tomatoes, firmness (85.2–86.8 N in PO364), total soluble solids (TSS: 3.9–4.3 °Brix), and low titratable acidity (TA: 5.2–6%) are essential for extended shelf life and consumer preference (Stevens *et al*., 1977). PO364's minimal weight loss (10–13%) and optimal TSS/TA balance align with the quality benchmarks (78–97 N firmness, 4.0–7.5 °Brix TSS) established by Sacco (2005), positioning it as a promising candidate for commercial cultivation.

3.2. Farmer Preference and Variety Performance

Based on farmers' preference, tomato hybrid variety PO364 emerged as the preferred variety in five locations (Meki-I, Meki-II, W/Genet, Dori, and Hawassa), while ranking second at Adami Tulu (Table 2). PO380 showed strong preference at Meki-II and Adami Tulu, consistently securing second place at the remaining sites. The control variety (Gelilea) consistently ranked third across all locations.

These preference rankings closely mirrored the agronomic performance observed in field trials, where both PO364 and PO380 demonstrated superior results across multiple evaluation parameters. While PO364 showed the strongest performance in controlled trials,

farmer selection criteria revealed a more nuanced decision-making process that extends beyond pure yield metrics. Farmers considered multiple factors based on their specific production needs and market requirements. The overall preference ranking clearly indicated PO364 as the top choice, followed by PO380, with Gelilea consistently rated as the least preferred option. This hierarchy reflects both the varieties' field performance and their alignment with farmer priorities across diverse production contexts.

Table 2: Farmers evaluation criteria of tomatoes, scores at the six sites, meaning of the scores and rankings (n= 6 farmers).

Location	**Variety**	**Criteria**									
		GP	FH	YP	FC	FS	DR	IR	MV	OAM	OAR
Meki-I	Gelilea	3	2	2	2	2	1	1	2	1.88	3rd
	PO364	3	3	2	3	3	3	3	3	2.88	1st
	PO380	2	1	2	2	3	3	3	2	2.25	2nd
Meki-II	Gelilea	2	1	2	3	3	1	2	2	2.00	2nd
	PO364	3	3	3	3	3	3	2	2	2.75	1st
	PO380	2	3	3	3	3	3	2	3	2.75	1st
A/Tulu	Gelilea	2	1	2	3	3	1	1	1	1.75	3rd
	PO364	2	2	3	2	3	2	2	3	2.38	2nd
	PO380	3	2	3	1	3	3	2	3	2.50	1st
W/Genet	Gelilea	2	3	2	2	3	1	2	3	2.25	3rd
	PO364	3	3	3	3	3	3	3	3	3.00	1st
	PO380	3	2	2	3	2	3	2	3	2.50	2nd
Dori	Gelilea	3	2	2	2	3	1	1	2	2.00	3rd
	PO364	3	3	3	3	3	3	2	3	2.88	1st
	PO380	2	2	1	3	3	3	2	2	2.25	2nd
Hawassa	Gelilea	1	1	2	1	3	1	1	2	1.50	3rd
	PO364	3	2	3	2	3	2	2	3	2.50	1st
	PO380	3	1	3	2	2	2	2	2	2.13	2nd

GP-Growth performance, FH-Frequency of harvest, YP-Yield potential, FC-Fruit color, FS-Fruit shape, DR-Disease resistance, IR-Insect resistant, MV-Market value, OAM-Over all mean and OAR-Over all rank

4. Conclusion and Recommendations

The overall results of the field study and farmers preference assessment indicate that tomato hybrid variety PO364 demonstrated superior performance across multiple parameters, including vegetative growth, yield, yield component fruit quality, and marketability, while PO380 showed competitive results, particularly in fruit size. Both varieties exhibited strong potential to enhance tomato productivity in the region. Given their high yield and quality traits, PO364 and PO380 shall be promoted and disseminated to smallholder farmers across the Rift Valley and other regions with similar agro-ecologies to boost tomato production. Further research should be conducted to assess the varieties' performance under diverse climatic conditions, including resistance to major diseases (e.g., late blight, powdery mildew) and pests (e.g., *Tuta absoluta*), to confirm their broader adaptability in Ethiopia.

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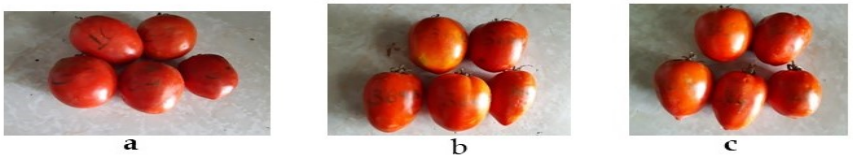
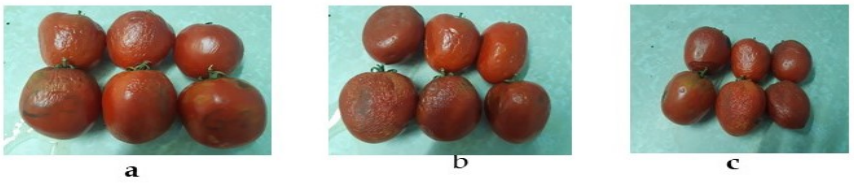
Annexes . The shelf-life performance of the tested varieties over time

Annex Figure-1: Pictures of the tomato fruits at 0 day storage



Annex Figure-2: Pictures of tomato fruits at 10 day storage- (a) PO364, (b) PO380 and (c) Gelilea



Annex Figure-3: Pictures of tomato fruits after 18 days storage at room temperature (20-22°C): (a) PO364, (b) PO380 and (c) Gelilea

Optimizing Seed Systems for Sustainable Productivity and Livelihoods in Northwest Ethiopia

Derbabaw Fentie Shiferaw*[1], Sintayehu Asmare[1,2,3],

[1]Department of Biological Science, University of Gondar, P.o.Box 196, Gondar
[2]Amhara Regional Agricultural Research Institute Seed Technology and Multiplication
[3]Bahir DarUniversity, College of Agriculture and Environmental Science
*Corresponding Author, Email derbabaw.fentie@uog.edu.et, derbabawf@gmail.com

Abstract

Agriculture is the backbone of Ethiopia's economy, with both highland and lowland crops playing a vital role in ensuring food security and economic stability. Crops such as barley, wheat, teff, sesame, sorghum, soybean, and mung bean significantly contribute to national productivity. This study explores seed systems for production, and protection while optimizing technology to support sustainable food systems across Ethiopia's diverse agro-ecological zones. Seed multiplication trials were conducted on highland and lowland crops, testing various seed classes under diverse conditions across multiple sites. Pre-harvest activities, including land preparation, sowing, fertilization, and weed control, were applied to enhance seed quality. Field inspections and quarantine measures ensured certification standards. The study revealed that seed yields varied across different crops and seed classes. Lowland crops, sesame yielded 773 kg/ha (Abasena, P/basic) and 381 kg/ha/ha (Gondar1). Sorghum (Melkam) produced 2,190 kg/ha (P/basic) and 3,480 kg/ha/ha (C1). Soybean (AFGAT) had the highest yield at 4,200 kg/ha, while Gishama yielded 1,925 kg/ha. Mung bean (Rasa) produced 850 kg/ha (basic). Highland crops, barley (IBON174/03) yielded 1,574 kg/ha/ha, food barley (Debark1) 7,636 kg/ha, and bread wheat (Alidero) 1,850 kg/ha/ha. Teff also showed promising yields. Seed quality varied, with sesame (99% purity, 98.25% germination, 2.2g/1000 seed weight), sorghum (99.3%, 85.25%, 30.4g), soybean (92.5%, 14.6g), and mung bean (99.4%, 80%, 5.4g). Strengthening both formal and informal systems, increasing research funding, and implementing robust policies are vital for improving productivity, food security, and climate resilience.

Keywords: Climate resilience, Crop productivity, Quality, Technology delivery

1. Introduction

The seed multiplication activities were implemented at four research stations under Gondar Agricultural Research Center (GARC) and UoG located in both highland and lowland agro-ecologies of the Amhara Region, Northwestern Ethiopia. The highland sites, Debark and Dabat, are situated at elevations ranging from 2,500 to 2,650 meters above sea level, with average annual rainfall between 1,200–1,400 mm and cool temperatures ranging from 6°C to 20°C. These conditions are highly suitable for temperate crops such as malt barley, food barley, bread wheat, and field pea. The dominant soil types are Nitisols, which are well-drained and rich in organic matter, enhancing seed quality and productivity.

The lowland sites, Metema and Tach Armachiho, lie at altitudes of around 750 meters above sea level, with semi-arid climatic conditions, receiving 850–1,100 mm of rainfall annually and experiencing higher temperatures between 20°C and 35°C. These agro-ecological conditions are ideal for seed multiplication of sesame, sorghum, soybean, and mung bean, under both rainfed and irrigated systems. The soils in these areas, mainly Vertisols and

Luvisols, are moderately fertile and responsive to fertilizer application, ensuring good seed yield. The diversity in agro-climatic conditions across these stations provides a robust basis to produce high-quality seeds adapted to both highland and lowland farming systems.

2. Materials and Methods

2.1. Seed multiplication procedures

Quality assured and certified seed classes were used as planting material, with recommended seed and fertilizer rates specific to each crop. Nutrient application included 121 kg/ha/ha of NPS and up to 100 kg/ha/ha of urea, with urea split into two doses to improve uptake. Manual weeding, timely rouging at critical growth stages (e.g., heading, flowering, and maturity), and internal and external field inspections (including quarantine oversight) ensured varietal purity and seed quality. At harvest, the crops were manually cut, threshed either by hand or using oxen, and then thoroughly cleaned. Clean seeds were packed in GARC-logo polypropylene bags and stored under controlled conditions at GARC facilities to maintain viability and vigor for subsequent seed multiplication.

2.2. Experimental design

The seed multiplication activities for both highland and lowland crops were conducted using a non-replicated field layout, which is appropriate for Early Generation Seed (EGS) production. The main objective was to maintain genetic purity, ensure uniformity, and produce high-quality seed rather than assess treatment effects. To support quality assurance and certification, each field was clearly demarcated by crops, variety, seed class, and location, with layouts designed to allow for effective field inspection, rouging, and harvest management.

Across all sites, a total of 19.37 hectares of lands were planted for seed multiplication during the cropping season. For highland crops, notable allocations included 0.38 ha for IBON174/03 malt barley (split between Debark and Dabat), 0.11 ha for Debark-1 food barley at Debark, 0.546 ha for Alidoro bread wheat (0.51 ha at Dabat, 0.036 ha at Debark), and 0.48 ha for Adi field pea (0.19 ha at Dabat, 0.29 ha at Debark). Meanwhile, lowland crops covered more extensive areas, with 2.53 hectares of Abasena sesame (pre-basic), 1.66 ha of Gondar-1 sesame (pre-basic), 1.36 hectarse of Melkam sorghum (P/basic), and 2.27 hectares (C1), 2.13 ha of Afgat soybean (pre-basic), 1.06 hectares (basic), and 2.5 hectares (irrigated). Gishama soybeans covered 1.47 hectares (pre-basic) and 1.95 hectares (basic). Mung bean (Rasa variety) was grown on 1.38 ha at Metema.

Spacing protocols followed crop-specific agronomic recommendations: 30 cm between rows for cereals and legumes (barley, wheat, pea), 40 cm for sesame and soybean, and 80 cm between rows and 15 cm between plants for sorghum. Isolation distances adhered to national seed standards, ranging from 5 meters for barley and legumes, to 200–250 meters for cross-pollinated crops like sesame and sorghum. Fertilizer applications were standardized, with most plots receiving 121 kg/ha of NPS and 100 kg/ha/ha of urea, split-applied to optimize nutrient availability.

This design enabled robust implementation of internal and external quarantine inspections, manual rouging at critical growth stages (e.g., flowering and maturity), and precise harvest

operations, ensuring the integrity and quality of early-generation seed across both agroecology.

3. Results and Discussion

3.1.Yield performance of seed multiplication models

The study assessed the effectiveness of different seed multiplication approaches—community-based and cooperative-led—on crop yield performance. Sorghum yields under community-based multiplication reached 3,480 kg/ha, while cooperative-led systems produced 2,190 kg/ha. For maize, yields were 4,200 kg/ha under community-based models compared to 3,600 kg/ha in cooperative settings.

These results align with findings of the Ethiopian Agricultural Transformation Institute (ATI, 2023), which reported that localized seed systems often outperform centralized models due to better agroecological matching and farmer ownership. The higher yields observed in community-based models suggest that decentralized seed multiplication can significantly enhance productivity when farmers have timely access to quality seeds adapted to local conditions.

The Early Generation Seed (EGS) multiplication activities conducted across highland and lowland agroecologies demonstrated successful implementation of technical standards and contributed significantly to seed supply systems in northwestern Ethiopia. A total of 19.37 hectares of land was allocated for the multiplication of seven key crops (barley, wheat, field pea, sesame, sorghum, soybean, and mung bean), with highland crops accounting for 1.52 ha and lowland crops covering 17.85 hectares.

3.2. Highland crops seed multiplication performance

The malt barley variety produced a yield of 840 kg/ha, with a seed purity of 99.3%, a germination rate of 97.7%, and a moisture content of 7.5%. These results are consistent with findings by (Tadele *et al.,* 2019), who noted that high purity and high germination rates are characteristic of barley varieties suitable for Ethiopia's highland areas. Malt barley is a high-value crop with good drought tolerance and can thrive under relatively low-input conditions, as also reported by (Seyfu *et al.,* 2017), who found similar high seed quality and yield when studying barley cultivation in Ethiopian highlands. The moisture content found in this study (7.5%) aligns with the standard for safe storage conditions, as recommended by [Bekele *et al*., 2018], who emphasized that barley seed moisture content should not exceed 8% to food barley. For food barley, the total yield obtained was 840 kg/ha, with a seed purity of 98.4%, a germination rate of 99.2%, and a moisture content of 7.5%. These results are in line with studies by (Tadesse *et al.,* 2020), which observed that food barley varieties typically exhibit high seed quality and germination potential. The results of the current study suggest that the food barley variety used is admirably adapted/adapted to highland conditions, where moisture is critical for seed development. Similar findings were reported by (Kebede *et al.,* 2015), who also highlighted the importance of high seed purity in ensuring the quality of food barley.

Bread wheat demonstrated a yield of 1,010 kg/ha, with a seed purity of 99.7%, a germination rate of 99.2% and moisture content of 10.95%. The results of this study are

comparable with (Hailu *et al.,* 2017), who found high yields and excellent seed quality in bread wheat grown in Ethiopia's highland regions. However, the slightly higher moisture content (10.95%) may raise concerns for storage and seed longevity, as the optimal moisture content for wheat seed storage should be below 10%, according to (Shiferaw *et al.,* 2019). This observation may require further investigation into post-harvest handling practices to ensure seed longevity and reduce spoilage.

The field pea variety yielded 168 kg/ha, with a seed purity of 98.2% and a germination rate of 85.5%. The results are slightly lower compared to other leguminous crops in similar studies, such as (Mekonnen *et al.,* 2018), who reported higher yields in field-pea under improved management practices. However, this variation may be attributed to the environmental conditions, as field peas are particularly sensitive to temperature and water stress during seed development. Despite the lower yield, the seed quality (purity of 98.2% and germination rate of 85.5%) is still within the acceptable range, as suggested by (Girma *et al.,* 2016).

Table 1: Seed Multiplication Results for Highland Crops

Crop Variety	eed Class	Yield (kg/ha)	Purity (%)	Germination (%)	Moisture Content (%)	1000 Seed Weight (g)
Malt -Barley	Pre-basic	840	99.3	97.7	7.5	-
Food -Barley	Pre-basic	840	98.4	99.2	7.5	44.3
Bread- Wheat	-	1010	99.7	99.2	10.95	43.5
Field- Pea	-	168	98.2	85.5	8.3	20.7

3.2.1. Lowland crop seed multiplication performance

The sesame yield for the Abasena variety was 773 kg/ha, and for Gondar1, it was 381 kg/ha. Both varieties exhibited high seed purity, with Abasena at 99% and Gondar1 at 98.7%. The germination rate for Abasena was 98.25%, and for Gondar1, it was 97.25%. These results are consistent with (Solomon *et al.,* 2020), who observed that sesame varieties grown in Ethiopia's lowland areas have high purity and germination rates. The moisture content was also relatively low (7.8%) for both varieties, which is in line with the recommendations by (Hussein *et al.,* 2017) for proper sesame seed storage. The yields reported in this study are lower than the potential yields observed in (Fikadu *et al.,* 2019), who reported up to 1,000 kg/ha/ha for sesame under improved management conditions.

Soybean: Soybean yields were significant, with the AFGAT variety producing 4,200 kg/ha and the Gishama variety producing 1,925 kg/ha. The seed purity for both varieties was excellent, with AFGAT at 99% and Gishama at 99%, and the germination rate for AFGAT was 97.7%, which aligns with findings by (Elias *et al.,* 2021) who observed similar high-quality seeds for soybean varieties grown in Ethiopia's lowland regions. The moisture content was also optimal at 7.5%. These results are in line with those of (Abayneh *et al.,* 2018), who reported high yields and good seed quality for soybean under irrigation in Ethiopia's lowland zones. However, the yield of Gishama was lower as compared to AFGAT, which is attributed to genetic differences and environmental factors, as discussed by (Getachew *et al.,* 2020).

Sorghum showed a varied performance depending on the seed class. The P/basic seed class yielded 2,190 kg/ha, while the C1 class yielded 3,480 kg/ha. The purity for P/basic was

99.2%, while C1 had a purity of 98.7%, with germination rates of 92.5% for P/basic and 84.4% for C1. These findings are like those of (Feleke *et al.,* 2019), who reported that sorghum varieties grown in Ethiopia's lowland regions exhibit high seed purity and acceptable germination rates. The results from this study suggest that sorghum is well-suited for lowland cultivation, where it benefits from warm temperatures and consistent moisture. However, further studies may be needed to determine the reasons for the variation in yield between seed classes, as highlighted by (Jemal *et al.,* 2018).

The mung bean variety Rasa produced a yield of 850 kg/ha, with a seed purity of 99.4% and a germination rate of 80%. These results are consistent with the findings of (Tadesse *et al.,* 2020), who reported that mung beans perform well under lowland conditions with high seed purity. However, the germination rate in this study was slightly lower than expected, as (Shenkute *et al.,* 2021) found a higher germination rate (85–90%) for mung beans under similar conditions. The relatively low germination rate in this trial may be attributed to seed handling or environmental stress during seed development.

Table 2: Seed Multiplication Results for Lowland Crops

Crop	Variety	Seed Class	Yield (kg/ha)	Purity (%)	Germination (%)	Moisture Content (%)	1000 Seed Weight (g)
Sesame	Abasena	Pre-basic	773	99.0	98.25	7.8	39.5
Sesame	Gondar1	Pre-basic	381	98.7	97.25	8.0	39.5
Soybean	AFGAT	Pre-basic	4200	99.0	97.7	7.5	39.5
Soybean	Gishama	P/basic	1925	99.0	85.0	7.8	39.5
Sorghum	Melkam	P/basic	2190	99.2	92.5	7.8	14.6
Sorghum	Melkam	C1	3480	98.7	84.4	7.8	27.3
Mung Bean	Rasa	Basic	850	99.4	80.0	-	5.4

3.2.2. Comparative analysis

The results from this study are generally consistent with findings from other studies on crop seed multiplication in Ethiopia. Highland crops like barley, wheat, and field pea are commonly reported to perform well in Ethiopia's cool highland regions, with high seed purity and germination rates, as noted in (Tadele *et al.,* 2019) and (Bekele *et al.,* 2018). Similarly, lowland crops like sesame, soybean, and sorghum are adapted to warmer climates, with high yields and good seed quality, as highlighted in (Elias *et al.,* 2021) and (Feleke *et al.,* 2019). The variations observed in this study, particularly with respect to yield and germination rates, can be attributed to differences in seed class, environmental factors, and management practices, which align with the observations made by (Getachew *et al.,* 2020) and (Shenkute *et al.,* 2021).

3.3. Broader implications for food security and farmer livelihoods

The yield improvements have direct implications for household food security. According to FAO (2021) estimates, the average Ethiopian household consumes approximately 200–250 kg of cereal per person per year. An additional 1,290 kg/ha of sorghum from community-based systems could feed five to six more individuals per hectare, reducing seasonal food shortages.

Moreover, surplus production enables farmers to engage in local markets. With sorghum selling at an average of ETB 12/kg in 2024 (CSA, 2024), the additional yield could generate ETB 15,480 per hectare, offering a meaningful boost to household income. This supports the World Bank's assertion that improving seed access is a key lever for poverty reduction in rural Ethiopia (World Bank, 2022).

3.4. Seed system efficiency and sustainability

The seed multiplication trials conducted in this study provide essential data for improving crop productivity and seed quality in Ethiopia's diverse agro-ecological zones. By ensuring high-quality seeds with good germination potential, the agricultural sector can improve its resilience to climate change, enhance food security, and boost farmers' incomes. The findings also underscore the importance of continued research and development to optimize seed multiplication systems and adapt crops to changing environmental conditions, as seen in the comparative analysis with other studies.

4. Conclusion and Recommendations

This study explored the performance and quality of seeds from both highland and lowland crops through systematic seed multiplication trials conducted in north Ethiopia. The findings demonstrate that crops such as malt barley, food barley, and bread wheat from the highland areas performed well, exhibiting high seed purity, excellent germination rates, and promising yields. Similarly, sesame, soybean, and sorghum from the lowland zones showed solid results in terms of yield, seed purity, and overall quality. The AFGAT soybean variety particularly stood out with impressive yields, which is essential for food security and agricultural sustainability in Ethiopia.

However, some crops, like field peas and mung beans, demonstrated less impressive results, especially in terms of seed quality and yield. The lower yield performance could be attributed to various factors such as seed variety, , or cultivation practices, which need further investigation. The findings of this study align with other research conducted in similar agro-ecological zones in Ethiopia, reinforcing the importance of both seed quality and management practices in ensuring high crop yields. The study highlights the potential for scaling up high-yielding varieties and improving seed production systems to boost agricultural productivity.

Improvement of Seed Multiplication Systems: To foster improved agricultural productivity, strengthening seed multiplication systems should be a priority. This includes enhancing both formal and informal seed production channels to ensure farmers have access to high-quality seeds. Training programs on best seed handling practices, better access to certified seeds, and improved agronomic knowledge will further empower farmers to achieve better yields.

Enhancement of Post-Harvest Handling Practices: The study revealed that seed moisture content was an issue in some crops, such as bread wheat, where the moisture content exceeded the desired threshold. This could compromise seed storage and longevity. It is recommended that farmers adopt more rigorous post-harvest handling techniques to reduce seed moisture content to below 10%, ensuring better seed storage and minimizing losses during storage.

Adoption of Crop-Specific Agronomic Practices: The variations in seed yields and quality across different crop types suggest that specific agronomic practices tailored to each crop's needs are essential. For instance, mung beans and field peas, which showed lower yield and quality, may require specific interventions such as improved irrigation, pest control, and soil management strategies. Research into crop-specific practices will be essential for optimizing yield and seed quality.

Continued Research and Investment in Seed Multiplication: To further improve the productivity of Ethiopia's agricultural sector, continued research on seed multiplication and crop performance is crucial. Research should focus on optimizing seed production techniques for various crops under diverse agro-ecological conditions, evaluating the effectiveness of different agronomic practices on crop yields and seed quality, and assessing the impact of environmental stress factors. The findings from such research will be invaluable for scaling up successful crop varieties and techniques. Fostering Multi-Stakeholder Collaboration: Successful seed multiplication and agricultural productivity improvements in Ethiopia require effective collaboration between various stakeholders, including government bodies, agricultural research institutions, NGOs, and farmers. Strengthening these partnerships will enable the sharing of knowledge, resources, and technology, creating a more integrated and efficient agricultural system that can respond to challenges such as climate change, food security, and poverty.

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On-Farm Evaluation of the Performance of Single Nutrient Source Fertilizer Application and Nitrogen Optimization on the Productivity of Teff in Tigray, Ethiopia

Tewolde Berhe*, Solomon Mebrahtom, Goitom Aregawi, Kinfe Tekulu, Tsadik Tadele, Samrawit Mebrahtu, Gebresemaeti Kahsu and Weldegebriel Gebrehiwot

Department of Soil Fertility Research, Shire Soil Research Centre, Tigray Agricultural Research Institute P.O. Box 40, Shire, Ethiopia
*Corresponding author: email: tewolde2004@gmail.com

Abstract

The cost of chemical fertilizer, especially urea, has increased in the face of environmental pollution and climate change. Therefore, this study aimed at evaluating the performance of P source and optimized N application rates with the existing fertilizer recommendation for enhanced productivity of teff. Field experiments were established in the cropping year of 2024 at four districts on teff crops following a randomized complete block design on 20 farmers' fields. The treatments were T1 (Negative Control, without fertilizer application), T2 (NPS + 100% recommended N with splits, 1/3 at planting and 2/3 at tillering), T3 (DAP+ 100% recommended N with splits, 1/3 at planting and 2/3 at tillering), T4 (TSP+ 100% recommended N splits, time, and methods of application), T5 (TSP+ 100% recommended N with splits zero at sowing + 2/3 beginning of tillering + 1/3 beginning of joining), T6 (TSP+ 75% recommended N with splits zero at sowing + ½ beginning of tillering + 1/2 at beginning of jointing). Our results revealed that plant height, panicle length, straw yield, biomass yield, and grain yield was significantly ($P<0.05$) influenced by N fertilizer rates with negative control. Thus, highest plant height (121.2cm), panicle length (45.7cm) obtained from plot treated through T2 (NPS + 100% recommended N) and grain yield (1692.3 kg ha^{-1}) were obtained from T5, (TSP+ 100% recommended N and the lowest value was recorded from unfertilized plot. Furthermore, the partial budget analysis indicated that the application of T5 (100 kg TSP + Rec. N (0,2/3,1/3) for production of teff was more economically beneficial for the study district. Our research encompassed only similar rates of nitrogen; hence, further research should be conducted at different rates of nitrogen and P sources on various soil and crop types.

Keyword: Partial budget, P source, split application, Teff

1. Introduction

Teff [*Eragrostis teff* (Zucc.) Trotter] is an indigenous staple crop in Ethiopia, cultivated long before the Semitic expansion (before 1000–4000 BC). (Melese *et al*., 2025) and covers 30% of the area and 20% of the total cereal production (CSA, 2017). Teff plays a great role in supplying society with protein, carbohydrates and minerals and it is a highly versatile crop with respect to adaptation to different agro-ecologies. It is widely grown between 1700 to 2400 meters above sea level (Refissa 2012 and Lemma 2022). However, teff has the lowest productivity compared to the other cereal crops as the national average yield is meager, ranging between 1.28 and 1.58 t ha^{-1} (CSA, 2017). Based on CSA (2022) report, Teff productivity and quality in Tigray is constrained by various factors of which environmental, genetics, management, capital, and input conditions are the most relevant.

The low availability of nitrogen and phosphorus has been demonstrated to be a major constraint to cereal production. Fertilizer usage plays a major role in the universal need to increase food production to meet the demands of the growing world population (Wezel *et al*., 2002). In most cases, high teff yield demands an increase in fertilizer application (Giller *et al.,* 2004). Nitrogen is the main yield limiting nutrient in Ethiopian agriculture and Urea as a source has been applied to correct its deficiency in the soil (Belete *et al*., 2018 and Omara *et al*., 2019). Thus, the cost of chemical fertilizer, especially urea, has gone up (CSA, 2022) with the face of environmental pollution and climate change. Thus, its use efficiency needs to be increased through optimization for sustainable crop production and productivity.

The use of fertilizers and efficient nutrient management can play key roles and closing the gap between actual and attainable yields thereby ensuring the national food security in Ethiopia. It is estimated that closing yield gaps to 100% of attainable yields could increase crop production at national level by thirty percent (30%) to forty-five percent (45%) for most major crops. Fundamentally, low yields are caused by deficiencies in the biophysical crop growth environment as the results of the current agricultural management practices. The average percentage of yield attributable to fertilizer is generally ranged from about 40 to 60% in Ethiopia and hence a rational use of fertilizer that can boost yield is necessary.

Food security cannot be accomplished without adequate N, P and K fertilization, which should be addressed simultaneously for the three nutrients. Straight fertilizer such as Urea, Triple superphosphate (TSP) and Muriate of potash (MOP) contains only one main nutrient although they may sometimes contain small quantities of other nutrients that help plants use the main one while compound fertilizers such as NPS and DAP contain more than one main nutrients. Therefore, with the straight fertilizers, the individual nutrient requirement of the crop can be met by supplying the required amount from the fertilizer with the intended nutrient. This opens opportunities for nutrient optimization unlike compound fertilizers as optimization targets only one nutrient which is difficult with compound fertilizers. It involves selecting the appropriate type of nutrient, applying at the optimal rate to meet crop needs without over-application and losses, and the application timing needs to coincide with plant growth stages where the crop can most effectively utilize it. Moreover, the unit cost of the various nutrients contained in the compound fertilizer will be higher when compared to the unit cost of nutrients contained in the straight fertilizers.

Nitrogen is a major yield-limiting nutrient in Ethiopian agriculture, with many soils deficient in plant-available nitrogen, and applying nitrogen fertilizer (e.g., urea) is key to increasing crop yields. However, applied nitrogen often exhibits low use efficiency, only 30–40% is harvested in grain while the rest is lost to the environment through leaching and runoff, leading to economic losses and environmental pollution. Therefore, improving nitrogen use efficiency through optimized fertilizer rates, timing, and integrated management practices is essential for sustainable crop production and productivity (Belete *et al*., 2018)

Nitrogen optimization involves saving some of the applied nutrient while maintaining optimum yield as well as increasing its efficiency by applying only when the crop needs N for its active growth (Tian *et al.,* 2020). Some literatures indicated that there is a need to apply half of the recommended Nitrogen during planting and half at 30-35 days after planting, but the use efficiency is below 50 % while some say after 2-3 weeks of planting assuming that the nitrogen in the seed is enough during planting (Zhang *et al.,* 2016 and Tian *et al.,* 2018).

Smaller N uptake capacity in the early growth of crops that can for instance be due to a small root population typically causes a large amount of applied N fertilizer to remain in the soil or even to be lost in the environment, resulting in reduced NUE (Jiang *et al.,* 2017). Therefore, this trial is trying to evaluate the performance of P source and optimized N applications rates with the existing fertilizer recommendation for increased fertilizer use efficiency and enhanced productivity in Ethiopia. Hence, this study aims to evaluate teff yield response to single nutrient source fertilizer applications (Urea and TSP) as compared with the reference formulas (NPS and DAP) and to assess the agronomic and economic benefits of single nutrient source fertilizer applications in optimizing N use under teff production.

2. Materials and Methods

2.1. Description of the study area

The study was conducted during the 2024/2025 main cropping season, during which a total of 20 on-farm trials were established in major teff-growing areas characterized by non-acidic soils in the central and north-western zones of Tigray, Ethiopia. To capture variability in dominant soil types, cropping systems, and agro-ecological conditions, the trials were implemented across four districts: Laelay Maichew and Tahtay Maichew in Central Tigray, and Laelay Koraro and Tahtay Koraro in North-Western Tigray, northern Ethiopia.

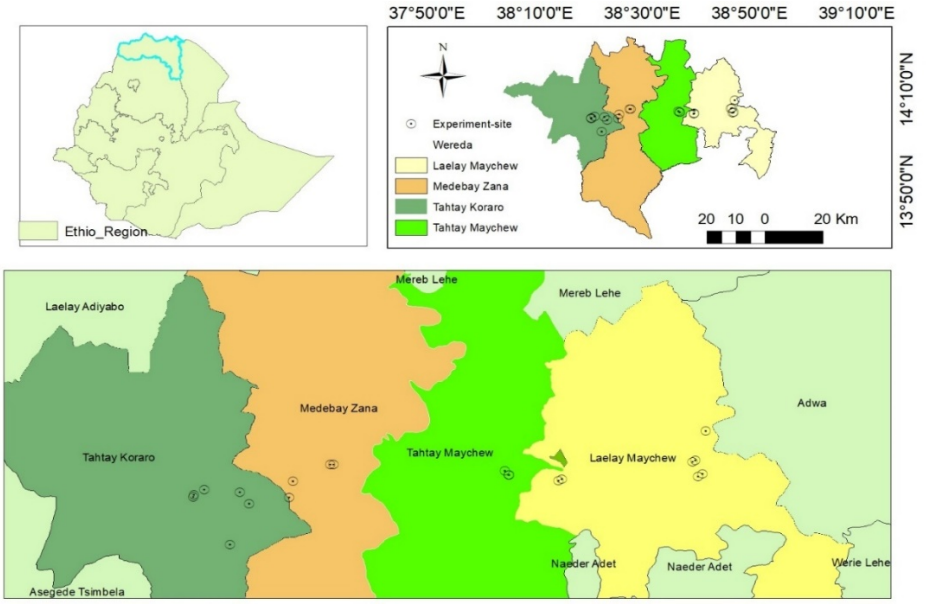

Figure 7: map of study area.

2.2. Experimental Materials

The field experiment was conducted on farmers' fields during the 2024 cropping season. The improved teff (*Eragrostis tef* [Zucc.] Trotter) variety **'Quncho'**, released by the Debre Zeit Agricultural Research Center (DZARC), Ethiopia, was used as the test crop. The variety is widely adapted and commonly grown in the study areas. Teff seed was sown by broadcasting at a seed rate of 15 kg ha^{-1}, which aligns with national recommendations.

Nitrogen (N) and phosphorus (P) fertilizers were used as the major nutrient sources. Nitrogen was applied following recommended split application schedules, while phosphorus fertilizers were applied at sowing time.

2.3. Treatments and Experimental Design

The experiment was laid out in a Randomized Complete Block Design (RCBD), in which farmers served as replications to capture field-level variability under on-farm conditions. Each experimental plot measured 5 m × 4 m (20 m^2). A spacing of 1 m between blocks and 0.5 m between plots was maintained to minimize nutrient movement and border effects.

Treatments consisted of different combinations of phosphorus fertilizer sources and nitrogen split application schedules, including a control (no fertilizer application). Treatments were randomly assigned to plots within each farmer's field.

The recommended fertilizer rates for teff in the study area were 69 kg N ha^{-1} and 46 kg P_2O_5 ha^{-1}. Phosphorus fertilizers were applied entirely at sowing by broadcasting, while nitrogen fertilizer was applied in split doses according to treatment specifications. Teff sowing was conducted between 11 and 29 July 2024, following the onset of the main rainy season.

2.4. Soil Sampling and Preparation Methods

Prior to planting, initial composite soil samples were collected from each on-farm trial field at a depth of 0–20 cm, which represents the effective rooting zone for teff. From each field, ten (10) soil sub-samples were taken using an auger in a zigzag pattern and thoroughly mixed to form one composite sample per farmer.

The collected soil samples were air-dried under shade, gently crushed, and passed through a 2-mm sieve to remove debris and coarse fragments. The samples prepared were then transported to the Shire Soil Research Center Analytical Laboratory for analysis.

2.5. Soil Analysis and Analytical Procedures

The processed soil samples were analyzed for selected physicochemical properties using standard laboratory procedures:

- Soil pH was determined in a 1:2.5 soil-to-water suspension using a digital pH meter, following the method described by Jackson (1973).
- Soil Organic Carbon (SOC) was analyzed using the Walkley and Black wet oxidation method (Walkley & Black, 1934).
- Total Nitrogen (TN) was determined using the Kjeldahl digestion method as outlined by Bremner and Mulvaney (1982).
- Available Phosphorus (P) was extracted using the Olsen method, suitable for neutral to alkaline soils, and measured colorimetrically using a spectrophotometer (Olsen *et al*., 1954).

Table 1: Treatment set up

Treatment No	Treatment name	Treatment Application
1	Negative Control	Without fertilizer application
2	Reference formula 1 (NPS + 100% recommended N)	100% recommended rate of P_2O_5 from NPS at sowing 100% recommended rate of N with urea splits, time, and methods of application.
3	Reference formula 2 (DAP+ 100% recommended N)	100% recommended rate of P_2O_5 from DAP at sowing 100% recommended rate of N with urea splits, time, and methods of application.
4	Differential Application-1 (TSP+ 100% recommended N)	100% recommended rate of P_2O_5 from TSP at sowing 100% recommended rate of N with urea splits, time, and methods of application.
5	Differential Application-2 (TSP+ 100% recommended N)	100% recommended rate of P_2O_5 from TSP at sowing 100% recommended rate of N with urea splits (zero at sowing + 2/3 beginning of tillering + 1/3 beginning of jointing).
6	Differential Application-3 (TSP+ 75% recommended N)	100% recommended rate of P_2O_5 from TSP at sowing 75% recommended rate of N with urea splits (zero at sowing + ½ beginning of tillering + 1/2 at beginning of jointing).

2.6. Crop data collection

Agronomic data was recorded on growth and yield related parameters of teff. These are biomass, grain and straw yield and yield components data such as plant height, and panicle length. Other additional parameters like days to 50% heading and days to 90% maturity (physiological maturity) were also recorded. Days to 50% heading were collected after 50% of the crop is thought to emerge and initiated heading respectively. Maturity was recorded when 90% of the plants attained (physiological maturity) as it was judged visually by observing the turning of the vegetative parts into yellow (straw) color. Plant height and panicle length were taken at this time using the tape meter.

Plant height and panicle length (cm): - Ten plants were randomly selected from central rows to measure plant height and panicle length. The measurement was from ground level to the tip of the main shoot panicle at maturity and the average was considered for statistical analysis.
Harvesting: was done from a $3.2m^2$ area (the net plot) after the crop finished its physiological maturity. Finally, data for biomass yield and grain yield was collected for each plot.

Above ground biomass (kg/ha): - Data for biomass yield was recorded from plants when the harvested biomass from the $3.2m^2$ area of each plot (net plots) is completely sun dried and attained constant weight which was converted to tons per hectare.

Grain yield (kg/ha): - Grain yield data for each plot was recorded by weighing the grain we get from each net plots after trashing/separating the seed from its straw and after the seeds are thought to be completely dried and finally the result was converted to tons per hectare. **Harvest index (%)**: - was calculated as ratio of grain yield per plot to the total above ground biomass yield per plot.

2.7.Economic Analysis

The partial budget analysis set by CIMMYT (1998) was followed to determine economic feasibility. Farm gate prices for the purchase of NPS and Urea and their respective application labor costs were considered as total variable costs (TVC) in the partial budget analysis. The teff grain and its straw yield were valued at an average open market price kg^{-1} (130 and 12 ETB respectively), cost of urea and NPS fertilizers were taken from the current market price. The labor for teff chemical fertilizer applications were also considered per person per day for a hectare of land. Furthermore, before computation, grain and straw yields of teff were adjusted downwards by 10% to represent the actual yield that can be obtainable under farmers' production practices.

2.8. Statistical analysis

Using the standard data analysis packages (SAS software), comparative advantage analysis was done, and mean separation was made using Tukey's HSD (Honestly Significant Difference). The one-way ANOVA model can be expressed as:

$$Y_{ij} = \mu + T_i + \varepsilon_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where,

Y_{ij} is the observed value for the j^{th} observation in the i^{th} group.

μ is the overall mean (grand mean) of all observations.

T_i is the effect of the i^{th} group (the difference between the mean of the i^{th} group and the grand mean).

ε_{ij} is the random error term, assumed to be normally distributed with a mean of 0 and a constant variance δ^2.

3. Results and Discussion

3.1. Soil characteristics of the study area

Selected physicochemical properties of soils of the study area were characterized based on the analytical results of the soil samples taken from the experimental fields before harvest (Table 2).

Table 2: Pre-sowing soil of study sites

District	Soil Properties							
	pH		SOC (%)		Ava P (ppm)		TN (%)	
	Max	Min	Max	Min	Max	Min	Max	Min
Laelay Maichew	7.56	7.02	0.85	0.42	7.58	17.97	0.16	0.12
Tehtay Maichew	7.05	7.03	0.82	0.78	5.60	7.60	0.19	0.16
Laelay Koraro	7.63	7.46	0.81	0.76	1.56	5.68	0.16	0.13
Tehatay Koraro	7.45	8.00	0.80	0.77	1.48	5.30	0.18	0.13

Where, max=maximum, min=minimum, SOC=soil organic carbon, Ava P=available phosphors, TN=total nitrogen

3.2. Effects of Nitrogen fertilizer rates on teff phenological characteristics

3.2.1.Days to 50% heading and Days to 90% physiological maturity

Days to 50% heading wasn't significantly ($p \leq 0.05$) affected by single nutrient source fertilizer application and N split application rather than with control plot (Table 3). The maximum number of days took the teff plant to reach 50% heading was observed on the control plots (with no fertilizer application). This result is in line with the findings of Sewnet (2005) who reported early flowering with an increase in the rate of N application in rice.

Table 3: Teff phenological and yield parameters as affected by Nitrogen fertilizer.

Treatment	Phenological and yield parameters of teff							
	DH	DM	PH	PL	BY	GY	SY	HI
Control	69.7 ^{c}	113.2^{b}	88.2^{b}	36.5b	4207.0^{b}	1146.5^{b}	3060.5^{b}	27.9^{a}
121 kg NPS + Rec. N (1/3rd, 2/3rd)	59.3^{a}	106.7^{a}	121.2^{a}	45.7a	7449.8^{a}	1458.8^{a}	5991^{a}	19.5^{c}
100 kg DAP + Rec. N (1/3rd, 2/3rd)	60.9 ^{a}	106.7^{a}	118.4 ^{a}	44a	7154.8 ^{a}	1547^{a}	5607.8^{a}	21.6^{bc}
100 kg TSP + Rec. N (1/3rd, 2/3rd)	62^{ab}	108^{ab}	117.6 ^{a}	44.7a	7032.8 ^{a}	1612.0 ^{a}	5487.5^{a}	21.7^{bc}
100 kg TSP + Rec. N (0,2/3rd,1/3rd)	64.6^{b}	108.3^{ab}	116.5 ^{a}	44.9a	7521.0 ^{a}	1692.3^{a}	5828.8^{a}	22.9^{b}
100 kg TSP + 75% of Rec. N applied (0, 1/2,1/2)	64.7^{b}	108.6^{ab}	114.2 ^{a}	44.78a	6971.8 ^{a}	1612.0^{a}	5359.8^{a}	23.8^{b}
Mean	63.5	108.52	112.8	43.4	6722.8	1500.3	5222.5	22.9
P-value	p≤0.0001	p≤0.017	p≤0.0001	p≤0.0001	p≤0.0001	p≤0.01	p≤0.0001	p≤0.0001
CV (%)	8.8	8	11	12.1	24	29	25.6	20.8

DH= days to 50% heading (days), DM= days to 90% maturity (days), PH= plant height (cm), PL= panicle length (cm), BY= biomass yield (kgha^{-1}), GY= grain yield (kgha^{-1}), SY= Straw Yield(kgha^{-1}), HI= Harvest Index (%)

Days to physiological maturity of teff was not vary significantly ($P \leq 0.05$) among fertilized plots. Hence, result of ANOVA table showed that physiological maturity control plot was not significant with treatments 4, 5, and 6, but statically vary with treatment 2 and 3.

3.2.2. Plant height and panicle length

The analysis of variance showed that there was no significant ($P \leq 0.05$) difference among the treatments on plant height and panicle length rather than with control plot. But the plots received fertilizer have highly significant difference with the control plot (Table 4). Plant

height increased with increasing application rates of the fertilizers. Thus, the highest plant height (121 cm) was obtained from the plot treated by 121 kg ha^{-1} NPS plus recommended N with split application 1/3 at sowing and 2/3 at tillering. In line with this study, Fenta A. (2018) reported a significant effect of increased N fertilizer on plants correlated with plant and panicle height. The plant height obtained from the all-treated plots was significantly higher than the unfertilized plot. This is because nitrogen fertilizer has a great role in plant growth.

The plant panicle length obtained from all treated plots was significantly higher (51cm) than the unfertilized plot but no significant difference between different treatments (Table 3). Many studies revealed significant influence of fertilizers on plant height as it plays a vital role in vegetative growth of plants. This may be attributed to the fact that N in the blended fertilizer favors vegetative growth of teff, resulting in higher stature of the plants with greater panicle length. In line with this finding, Legesse (2004) reported that application of higher fertilizer rates resulted in teff plants with significantly taller panicle due to direct effect of N on vegetative growth of crop plants.

3.3. Effects of Single nutrient and Nitrogen fertilizer on teff yield and yield components.

3.3.1. Biomass yield

Aboveground dry biomass yield was not significantly ($P \leq 0.05$) influenced by the treatments. But there was highly significant difference between fertilized plots and the control plot. This result showed 41.4% dry above biomass yield increment over unfertilized plot (Table 3). Biological yield is a function of photosynthetic rate and proportion of the assimilatory surface area. Hence, the increase in biological yield with increase in rate of NPS and N fertilizer might be due to N and S integrated effect for better vegetative growth of crops, which ultimately produced more biological yield.

3.3.2. Grain yield

The analysis revealed that the specific strategy of fertilizer application did not statistically alter grain production. Whether fertilizers were applied as single-nutrient sources or through a split application of nitrogen, the resulting grain yields were not significantly different ($p < 0.05$) from the unfertilized control plots. This indicates that, for grain yield specifically, the tested application methods did not provide a measurable advantage over no fertilization under the conditions of this experiment.

3.3.3. Straw Yield

The results for straw yield presented a more layered finding. When comparing all individual treatment methods against each other, no single fertilizer treatment significantly outperformed another. However, a critical and highly significant pattern emerged when all fertilized plots were evaluated as a group against control. Plots that received any form of fertilizer produced substantially more straw biomass than those left unfertilized. This was clearly demonstrated by the control plots, which yielded the absolute minimum straw yield of 1146.5 units.

3.3.4. Harvest index

The effect of different fertilizers on teff was highly significant ($P \leq 0.05$) affected harvest index (Table 3). Harvest index decreased with increased rates of fertilizers. The highest HI was scored from the control plots (0 kg ha^{-1}) and the lowest HI was obtained on plot treated by 121 kg ha^{-1} NPS and recommended N fertilizer with split application 1/3 at sowing and 2/3 at tillering (Table 3). Similar to this study Mulugeta (2003) found the lowest harvest index when the highest N rate was applied as compared to the control treatment on teff.

3.4. Economic analysis

Partial budget analysis indicated that the highest net benefit (254,247 ETB ha^{-1}) and the highest marginal rate of return (MRR) (402%) was obtained from the fertilizer application of T5 (100 kg TSP + Rec. N (0,2/3,1/3)**.** The MRR indicated that teff producers can get an extra of 4.02 ETB for every 1.00 ETB investment in the application of T3 (100 kg TSP + Rec. N (0,1/3,2/3)), over that of T2 (100 kg TSP + 75% of Rec. N applied (0, 1/2,1/2)), which had a MRR of 13.28 ETB for 1.00 ETB investment. Therefore, the application of this treatment to produce teff was more economically beneficial.

Table 4: Dominance analysis as affected by Nitrogen fertilizer.

Fertilizer rate (kg ha^{-1})	TVC [Birr]	AjY (kg ha^{-1})	SY (kg ha^{-1})	TR [Birr]	NR [Birr]	Dominance (D)	MRR (ratio)	MRR (%)
Control	0.00	1032	3060.5	168142.655	168143			
100 kg TSP + 75% of Rec. N applied (0, 1/2,1/2)	5602.58	1451	5359.8	248151.378	242549		13.28	1328
100 kg TSP + Rec. N (0,2/3,1/3)	8510.40	1523	5828.8	262757.068	254247		4.02	402
100 kg TSP + Rec. N (1/3, 2/3)	8510.40	1391	5487.5	241766.225	233256	D		
100 kg DAP + Rec. N (1/3, 2/3)	9593.59	1392	5607.8	243301.658	233708	D		
121 kg NPS + Rec. N (1/3, 2/3)	11474.64	1313	5991	237239.61	225765	D		

Where TVC= total variable cost, AdjY= adjusted yield, SY= straw yield, TR= total revenue, NR= net revenue MRR= marginal rate of return

4. Conclusion and Recommendations

Teff phenological traits and yield parameters were significantly influenced by split application of nitrogen fertilizer compared with the control treatment, although differences among the nitrogen treatments themselves were not statistically significant. The highest plant height (121.2 cm) and panicle length (45.7 cm) were recorded from plots treated with T2 (121 kg NPS + 100% of the recommended nitrogen rate applied in split doses: 1/3 at sowing and 2/3 at tillering). In contrast, the highest grain yield (1692.3 kg ha^{-1}) was obtained from plots treated with T5 (100 kg TSP + 100% of the recommended nitrogen rate applied as 0 at sowing, 2/3 at tillering, and 1/3 at jointing stages).

Furthermore, partial budget analysis indicated that the T5 treatment (100 kg TSP combined with split application of the recommended nitrogen rate at 0, 2/3, and 1/3 proportions) was the most economically profitable option for teff production in the study districts.

Based on the findings of this study, the following recommendations are suggested. First, Since the current study evaluated similar nitrogen rates, further on-farm research should be conducted using varying nitrogen rates and different phosphorus sources across diverse soil types and cropping systems. Second, additional studies are recommended to investigate the individual and combined effects of nitrogen application rate and timing across multiple locations and seasons to enhance the robustness and wider applicability of the results.

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Effects of Agricultural Lime and Blended NPSB Fertilizer Application on the Productivity of Wheat (Triticum aestivum L.) and Soil Properties in Hulbarag Woreda, Silte Zone, Central Ethiopia

Alemu Lelago*, Awel Jemal and Mesfin Kassa

Wolaita Sodo University, College of Agriculture, Department of Plant Sciences
*Corresponding author email: lelagoalemu@gmail.com

Abstract

This research addresses a key constraint to bread wheat productivity in Ethiopia, particularly in Hulbarag District: low soil fertility and acidity. A field experiment was conducted during the 2022 main cropping season to evaluate the effects of agricultural lime and blended NPSB fertilizer on wheat yield and to determine the most economically viable application rates. The experiment tested five lime rates (0 to 7348 kg ha^{-1}) and four NPSB fertilizer rates (0 to 150 kg ha^{-1}) in a factorial arrangement. The results demonstrated that applying lime and NPSB significantly improved key soil properties, increasing available phosphorus (P), sulfur (S), organic carbon (OC), and exchangeable bases (Mg, Ca, Na, K), while reducing the concentration of micronutrients like Fe, B, Zn, Mn, and Cu in the soil. Furthermore, both inputs had a significant positive effect on wheat growth and yield components. Plant height, spike length, thousand-kernel weight, above-ground dry biomass, grain yield, and straw yield were all enhanced. The highest productivity was achieved with the combined application of 7348 kg ha^{-1} of lime and 150 kg ha^{-1} of NPSB, which yielded 5940 kg ha^{-1} of grain and 12,165 kg ha^{-1} of biomass. An economic analysis confirmed that this same treatment combination was the most profitable. It delivered the highest net benefit (189,773 Birr ha^{-1}) with a remarkable marginal rate of return (MRR) of 2,293%, far exceeding the acceptable minimum threshold of 100%. In conclusion, the study confirms that the strategic use of agricultural lime and blended NPSB fertilizer is a highly effective and economically attractive approach for improving soil health and significantly boosting the yield and profitability of bread wheat production in the study area.

Keywords: Biomass; economic benefit; grain yield; Soil nutrient concentration

1. Introduction

Wheat (*Triticum aestivum* L.*) is o*ne of the most important highland cereal crops globally utilized for both food and animal feed. According to Minot *et al*. (2019), Ethiopia is one of the major producers of wheat in sub-Saharan Africa. FAO (2012) estimated that in 2010, Ethiopia produced wheat on 217 million hectares (ha) of land, and the average productivity was around 3 tons per hectare (tha^{-1}). In Ethiopia, wheat is the most important grain crop and is especially popular in metropolitan areas. It ranks second behind maize and slightly ahead of teff, sorghum, and enset, each contributing 10-12% of the calorie intake for its over 90 million population (Senbeta and Worku, 2023). It contributes about 15% of the caloric intake for these countries. Ethiopia is sub-Saharan Africa's second-largest wheat producer, behind South Africa (Samuel *et al*., 2017).

As stated by FAO (2012), the main yield-limiting factors include low soil fertility, low input levels, such as fertilizer and high-quality seed, and soil chemical deterioration, mainly due

to soil acidity. In Ethiopia, it was estimated that soil acidity affected around 40.9% of the country's arable land, out of which about 27.7% moderately acidic (pH 4.5-5.5) and 13.2% extremely acidic (pH 4.5) (EthioSIS, 2013).

As a result of nutrient mining by the traditional farming system and inefficient and imbalanced fertilizer application, multi-nutrient insufficiency is common in Ethiopian soils (Agegnehu *et al.,*2019; Zeleke *et al.,*2010). Assuming that nitrogen and phosphorus are the main limiting nutrients in Ethiopian soils, the only chemical fertilizers employed for crop production are urea and di-ammonium phosphate (DAP) (Bekabil and Hassan, 2006). However, in addition to N and phosphorus (P), many soils in Ethiopia are poor in sulfur (S), boron (B), and zinc (Zn), and some are also deficient in potassium (K), copper (Cu), manganese (Mn), and iron (Fe), which could reduce crop yield and nutritional quality of food and feed crops (EthioSIS,2013).

To guarantee that crops receive all or majority of the nutrients they require, a variety of fertilizer combinations would be required. Without sulfur, the amino acids cysteine, and methionine cannot be formed. Further, N uptake is improved when sulfur is introduced, indicating a synergistic interaction between the two nutrients (Fernando *et al*., 2009). Furthermore, plants require boron for enhanced absorption of macronutrients, which enhances the transfer of photo assimilates during their different development stages from source to sink (Ali *et al*., 2013).

One of the main causes of land deterioration, soil acidity, affects over 50% of the world's potentially arable soil (Kochian *et al*.,2004). Because acidic soils have dangerous levels of aluminum and manganese and lacks vital plant nutrients like P, N, K, Ca, Mg, and Mo when the pH of the soil drops below 5.5, it has an impact on the growth of crops. Al interferes with the uptake, transport, and utilization of vital plant nutrients such as P, K, Ca, Mg, and water, as well as enzyme activity in the roots, making excessive Al concentrations detrimental to plant roots Al (Baquy *et al*., 2017).

One of the most significant issues in soil acidity, which is made worse by heavy rainfall and results in the leaching of exchangeable base cations from the soil surface (Chimdi *et al*., 2012). The toxicity levels depend on how much soluble or exchangeable Al^{3+} are present and how acidic the pH is (Crawford *et al*.,2008). When paired with iron oxide and aluminum oxide at pH 5.0, soil acidity can also decrease the availability of phosphorus by producing insoluble compounds (Chude *et al*., 2004).

Along with other physicochemical and biological processes, vast volumes of carbonic acid produced by microbes and higher plants are what cause soil acidity. However, the effect of its dissociation is very minimal because the majority of it is lost to the atmosphere as CO_2 (Kochian *et al*., 2004). Continuously applying inorganic fertilizer without first conducting a soil test may ultimately result in a rise in soil acidity. The use of nitrogen fertilizers in ammonia form is another source of acidification (Fageria and Nascente, 2014; Guo *et al*., 2010).

Agricultural lime (ag lime) application on acidic soils increases availability of crucial nutrients (Ca, P, and Mo), nitrogen fixation by rhizobium symbiosis, and decreases the solubility of toxic elements such as Al and Mn in the soil. Thus, it has been suggested as an effective

measure to ameliorate acidic soils for cultivation of crops in highland areas (Crawford *et al*., 2008).

A factorial experiment was conducted at Angamo yede FTC in Hulbarag district of Silte zone, Central Ethiopia region to address the problem of soil acidity using a combination of different rates of ag lime and blended NPSB fertilizer. The altitude of the study area ranges from 2118 to 2463 m.a.s.l. and has high annual rainfall (> 1200 mm), which has exposed the region to soil erosion aggravated by its dense population, lack of farmland, ongoing land cultivation, and frequent application of inorganic fertilizer, In the area, soil fertility levels are decreasing and basic nutrients like calcium, magnesium, phosphorous, and potassium are deficient while toxic nutrients such as aluminum and manganese are still present (EthioSIS, 2013). As a result, important crops like wheat do not receive crucial nutrients necessary for its growth.

The main factors causing soil acidity in the study area include climatic factors such as high amount of precipitation (that exceeds evapotranspiration which leaches appreciable amounts of exchangeable bases from the surface soil), temperature, and severe soil erosion, morphological and anthropological factors *(*Temesgen *et al*., 2011). In this case, repeated plowing of land is taking place, and essential basic cations are eroded, leached down to the ground or used by crop plants. Wheat and other crop productivity have become unusually low. High acidity in soils is caused by a shortage of available Ca, P and Mo and an excess of soluble Al, Mn and other metallic ions *(*Fageria and Nascente, 2014). Acid soil limits the availability of crucial nutrients such as P, K, Ca, and Mg and limits presence of important soil organism's plants need to stay healthy. If a particular soil is too acidic for plants to grow healthy, it is necessary to raise the pH by applying an alkaline substance. The yields of crops grown on acidic soil are very low. Consequently, the youth and elderly of the area have migrated to other areas inside or outside of the country in search of alternative livelihoods. To tackle this problem, it is necessary to improve the quality of the soils in the *Angamo yede* area to increase the productivity of food crops. Thus, this experiment was conducted to evaluate the effects of treating acidic soils with a combination of different rates of ag lime and blended NPSB fertilizer on growth and productivity of wheat in the study area.

2. Materials and Methods

2.1. Descriptions of the study area

The study was conducted in Hulbarag District, which is found in Silte Zone. The area is found 15 km south-west of Worabe town, the capital of the Silte zone, and 188 km from Addis Ababa. The absolute location of the study area is at 7^{o} 35' 10" to 7^{o} 54'10"N and from 37^{0} 56' 0" to 38^{0} 21' 30" E latitude and longitude, respectively. The average temperature of the area is 24 ^{o}C, the average annual rainfall is 1200 mm, and the average elevation of the study area is 2142 m.a.s.l. The soil of the experimental site is classified as sandy loam in texture. Hulbarag District has a wide range of agro-ecological conditions, including hot arid and semi-arid climates (*kola*) in the south and temperate or highlands (*dega* and *kefil-wirch*) in the north and northwest. The climate of the area is classified as tropical sub-humid (*woinadega).* 48% of the district is moderately suitable for settlement and crop production. Most parts of the district, about 90.5% lie under the *woinadega* types of agro-ecology, while *dega* and *wurch* conditions make these districts endowed with the production of different commercial and food crops. The district is characterized by a subsistence mixed farming system where

production of both crops and livestock are common economic activities. Due to the varied agro-ecologies of the area, major crops growing include cereals, legumes, vegetables, root crops, perennials fruits, etc. Commonly produced crops in the area include wheat, maize, *teff* and coffee, root crops such as sweet potato, yam, potato, *enset*, and fruits (Haile *et al*., 2012).

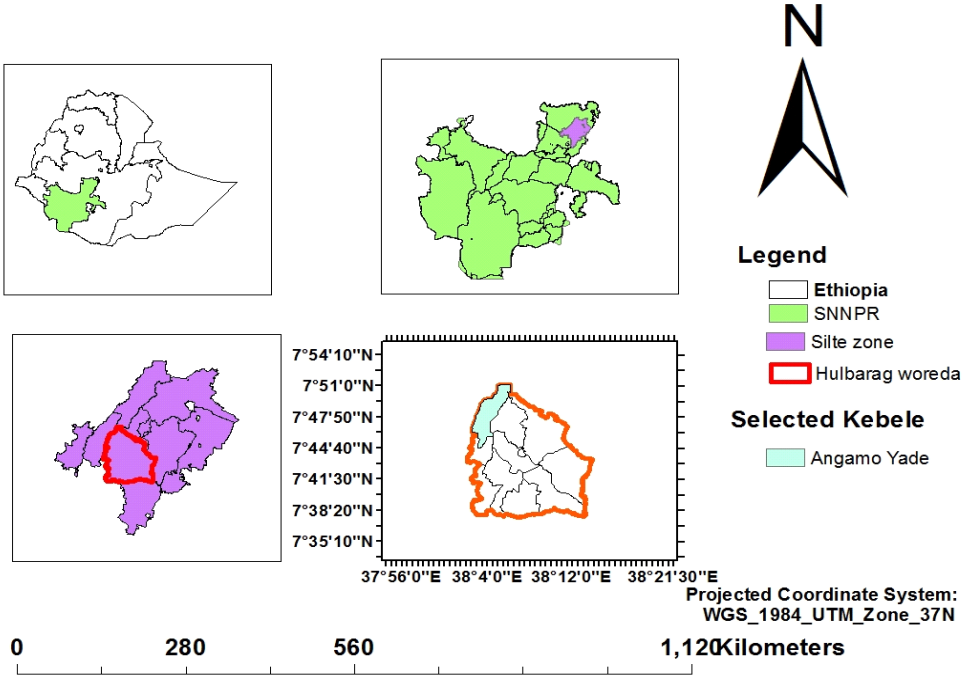

Figure 1. Map of study area.

2.2. Experimental design

Ogolcho wheat variety was used for experimentation and sown by drilling at a seeding rate of 100 kgha^{-1}. The total area of the research site was 14 m x 26 m, or 364 m^2, and the area was divided into three blocks, each block divided into twenty (20) plots. The area of one plot was 1.2m x 3m = 3.6 m^2, and the area of one block was 8m x 14m = 112 m^2. The space between blocks was 1 meter, and the space between plots was 0.5 meter. The experiment was laid out in a randomized complete block design (RCBD) arranged in a complete factorial with five levels of lime (0, 1837, 3674, 5511, and 7348 kgha^{-1}) and 4 different rates of NPSB (0, 50, 100, and 150 kgha-1) and 100 kgha-1 of urea (was applied to each prepared plot uniformly. From the total urea fertilizer, 2/3 was applied during final land preparation, and the rest, 1/3, was applied 20 days after sowing. The NPSB fertilizer was incorporated into the soil earlier one day before sowing, and the ag lime was applied one month earlier and incorporated into the soil. The ag lime requirement of the soil was calculated based on its exchangeable acidity (Al^{+3} and H^{+1}). The following formula was used to determine the lime requirement (Lierop, 1983):

Lime requirement (LR).LR $CaCO_{3\ (kg/ha)} = \frac{EA\left(\frac{cmol}{Kg}\right) * 0.15m * 104m2 * B.D(g/cm3)}{2000} * 1000$

Where,

EA = Exchangeable acidity ($H^+ + Al^{3+}$)
LR= Lime Requirements, 0.15 m = plow depth/depth of lime incorporation.
2000 = Conversion factor to convert exchangeable acidity per kg of soil to per hectare.
BD – Bulk Density

2.3. Treatments

The fertilizer treatments consisted of four rates of NPSB (0, 50, 100 and 150 kga^{-1}). The middle rates of NPSB fertilizer were fixed based on the recommendation given by the Ethiopian Institute of Agricultural Research (EIAR) for faba bean production (EIAR, 2018). Urea [$CO(NH_2)_2$] (46% N) was used as a source of nitrogen and applied on all treatments at a rate of 100 $kgha^{-1}$, except for the control treatment. The experiment was laid out as a randomized complete block design in a factorial arrangement and replicated three times per treatment.

2.4. Yield and yield components

Number of total tillers: The number of total tillers was determined from 0.5 m of row length from two rows per net plot at physiological maturity by counting the number of tillers.

Number of productive tillers: The number of productive tillers was determined at maturity by counting all spikes bearing kernels from two rows of 0.5 m length per plot at physiological maturity.

Number of kernels per spike: The mean number of kernels per spike was computed as an average of 10 randomly taken spikes from the net plot area.

Thousand kernels weight (g): The thousand kernels weight was determined based on the weight of 1000 kernels sampled from the grain yield of each net plot by counting using an electronic seed counter and weighing with a sensitive balance. Then the weight was adjusted to 12.5% moisture content.

Above ground dry biomass (t ha^{-1}): The above ground dry biomass was determined from plants harvested from the net plot area after sun drying to a constant weight and converted to tons per hectare.

Grain yield (t ha^{-1}): Grain yield was taken by harvesting and threshing the seed yield from the net plot area. The yield was adjusted to 12.5% moisture content. Finally, yield per plot was converted to a per-hectare basis, and the average yield was reported in t ha^{-1}.

Adjusted grain yield= $$\frac{(100-\mathrm{MC})*\text{unadjusted grain yield}}{100-12.5}$$

Straw yield (t ha^{-1}): Straw yield was obtained as the difference between the total above ground dry biomass and grain yield.

Harvest index (%): The harvest index was calculated as the ratio of grain yield per plot to total above ground dry biomass yield per plot expressed as a percentage.

2.5. Partial budget analysis

The economic analysis was carried out using the methodology described in CIMMYT (1988) in which prevailing market prices for inputs at planting and for outputs at harvesting were used. All costs and benefits were calculated on aper-ha basis in Birr. The concepts used in the partial budget analysis were the mean grain yield of each treatment, the gross benefit (GB) ha^{-1} (the mean yield for each treatment), and the field price of fertilizers (the costs of NPSB, seed, and application costs). The marginal rate of return, which refers to net income obtained by incurring a unit cost of fertilizer, was calculated by dividing the net increase in yield of wheat due to the application of NPSB fertilizers and ag lime. The net benefit (NB) was calculated as the difference between the gross benefit and the total cost that varies (TCV) using the formula: NB = (GY x P) – TCV.

Where GY x P = Gross Field Benefit (GFB), GY = Adjusted Grain yield per hectare, and P = Field price per unit of the crop. For each pair of ranked treatments, % marginal rate of return (MRR) was calculated using the formula:

$$\textbf{MRR (\%)} = \frac{Change\ in\ NB(NBb - NBa)}{Change\ in\ TCV(TCVb - TCVa)} * 100$$

Where, NBa = NB with the immediate lower TCV, NBb = NB with the next higher TCV, TCVa = the immediate lower TCV and TCVb = the next highest TCV

2.6. Statistical analysis

Analysis of variance (ANOVA) was carried out using Statistic software version 8.0, as described by Gomez and Gomez (1984) to differentiate the extent of relations between treatments. Whenever a significant difference among treatments is detected, mean separation is done using the least significant difference (LSD) test at a 5% probability level. Besides, descriptive statistics and correlation analysis were employed. Physical and chemical soil characteristics were determined from composite soil samples collected from 0–20 cm depth for the initial determination of soil fertility parameters.

3. Results and Discussion

3.1. Yield and yield components

3.1.1. Number of total tillers and productive tillers

The analysis of variance indicated that the main effects of ag lime and blended NPSB fertilizer rates had highly significant ($p<0.05$) effects on the number of total and effective tillers per plant. The treatment with the largest amount of ag lime (7348 kgha-1) and the largest amount of NPSB fertilizer (150 kg/ha) achieved a large number of total tillers and productive tillers (580 and 490), respectively, and the lowest number of total tillers and productive tillers were recorded at the control (148 and 84, respectively). Higher numbers of effective tillers and total tillers were obtained with the application of 0.611t ag lime, 2.5 t compost, 75 kg NPSB, 50 kg KCl, and 36 kg N ha^{-1} compared with the control (Woubshet *et al.,* 2017).

In line with this result, Hameed *et al.* (2003) observed that increasing nitrogen application significantly increased the number of tillers per m^2. Pasha (2005) also found a significant

increase in the number of total tillers per plant with the increase in NPK level from 0 to 150 kgha^{-1}. Similarly, Temesgen *et al*. (2011) reported that significant variations in the number of tillers per plant with the increased level of phosphorus application and the maximum number of tillers per plant (6.67) were found at 80 kgha^{-1} P.

3.1.2. Number of kernels per spike

The result revealed that fertilizer rates showed a highly significant ($p< 0.05$) effect with respect to the number of kernels per spike. The treatment with the largest amount of ag lime (7348 kgha^{-1}) and the largest amount of fertilizer (150 kgha^{-1}) achieved a large number of kernels per spike (89.667), and the lowest number of kernels per spike was recorded at the control (26.533). The number of kernels per spike of barley were significantly affected by the integrated use of ag lime and nutrients. In line with this, a higher mean spike length (7cm) and number of kernels per spike of barley were obtained with the integrated application of 611 kg ag lime + 5 t compost + 150 kg NPSB + 100 kg KCl + 72 kg N ha^{-1}. This gave an advantage of a 23 and 53% increase in spike length and number of kernels per spike of barley respectively, as compared to control plots (Woubshet *et al.,* 2017). The possible reason for the increased number of kernels per spike could be that mineral fertilizer and the mineralization of organic nutrient sources due to the effect of liming didn't put the plants under nutrient stress at any stage throughout the growing season. Similarly, Jan and Khan (2000) and Marschner (2011) observed significant effects of nitrogen application on grain number per spike, significant increase in number of grains per spike with each increment of NPK fertilizer, respectively. Geleto *et al.* (1995) also reported a higher number of spikes per unit area at 120 kg N ha^{-1} fertilized plots than the control.

3.1.3. Thousand kernels weight (TKW)

The result revealed that ag lime, fertilizer rate, and the inversion of the two main factors were highly significant ($p<0.05$). The treatment with the largest amount of ag lime (7348 kgha^{-1}) and the largest amount of NPSB fertilizer (150 kgha-1) achieved a large amount of a thousand kernel weight of 51.433 g, and the lowest thousand kernel weight recorded at the control was 33.533 g.

The highest thousand seed weight of barley (44 g) was recorded with the application of 0.611 t lime + 5 t compost + 150 kg NPSB + 100 kg KCl + 72 kg N ha^{-1}, followed by 43 g with the application of 611 t lime + 2.5 t compost + 75 kg NPSB + 50 kg KCl + 36 kg N ha^{-1} over control plots (10 g), which is attributed to better availability of nutrients. The lowest thousand seeds weight could be due to shriveled seeds that have small sizes, which contributed to the lower grain weight. Increase in the combination of ag lime, organic, and inorganic fertilizers increased the thousand seed weight of barley from 10 g to 44 g (Woubshet *et al.,* 2017). A higher amount of nitrogen application resulted in a higher percentage of weight gain in the grain-filling stage of kernels, and thereby, the kernel weight increased by 1,000 (Marschner,2011). Makowski *al.* (2008) also reported that 1000 kernels weight increased with the increase in nitrogen rate up to 100 kgha^{-1}.

Table 1. Effect of the interaction Lime and blended NPSB fertilizer on yield and yield component

Lime	NPSB	NTT	NPT	NKPS	TKW
0	0	145.00 ^{j}	113.51^{k}	26.112^{h}	33.533^{j}
0	50	201.33 ^{hij}	120.83^{jk}	35.563^{h}	34.167^{ij}
0	100	217.67^{ghi}	123.83^{jk}	38.229^{g}	34.867^{hij}
0	150	194.33^{hij}	128.16^{jk}	40.963^{fg}	35.300^{ghij}
1837	0	165.00^{ij}	144.83^{ijk}	42.563^{fg}	35.867^{fghij}
1837	50	209.00^{ghij}	151.50^{ijk}	43.563^{efg}	36.667^{efghij}
1837	100	214.33^{ghi}	159.50^{hij}	43.563^{efg}	37.233^{defghij}
1837	150	246.33^{fgh}	166.16g^{hij}	43.163^{efg}	37.333^{defghi}
3674	0	220.00^{ghi}	182.16^{fghi}	36.629^{gh}	37.700^{cdefghi}
3674	50	257.67^{fgh}	190.16^{efghi}	47.296^{defg}	37.833^{cdefghi}
3674	100	270.33^{fg}	198.16^{efgh}	46.629^{defg}	38.233^{cdefgh}
3674	150	299.33^{def}	204.83^{efgh}	52.763^{cdef}	38.533^{cdefgh}
5511	0	247.67^{fgh}	210.16^{efg}	54.896^{cde}	38.700^{cdefg}
5511	50	311.00^{def}	223.50^{ef}	56.296^{cd}	39.467^{cdef}
5511	100	338.67^{cde}	230.83^{de}	59.696^{bc}	39.533^{cdef}
5511	150	362.00^{cd}	271.50^{cd}	53.029^{cdef}	40.400^{cde}
7348	0	291.00^{ef}	276.50^{cd}	58.563^{bcd}	40.567^{cd}
7348	50	395.33^{bc}	284.83^{c}	60.763^{bc}	41.167^{bc}
7348	100	434.33 ^{b}	332.16^{b}	69.496^{b}	44.767^{b}
7348	150	541.67^{a}	412.50^{a}	90.563^{a}	51.433^{a}
LSD		-	-	-	1.8668
CV		14.69	13.44	14.60	5.91

Means in columns and rows followed by the same letters are not significantly different at 5% level of significance; LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of variation

3.1.4. Grain yield (kgha-1)

The analysis of variance showed that the main effects of ag lime and blended NPSB fertilizer and their interactions are significantly different ($P < 0.05$). The treatment with the largest amounts of ag lime (7348 kgha^{-1}) and NPSB fertilizer (150 kgha^{-1}) had the largest yield of 5940 kgha^{-1}of grain, and the lowest yield with the control was 2383.3 kgha^{-1} of wheat as shown above (Table 1). In line with this result, Temesgen *et al*. (2017) found that 1.65 t/ha ag lime and 20 kgha^{-1} phosphorus application could give a profitable yield, which was on par with the application of 2.2 t/ha ag lime and 30 kgha^{-1} phosphorus, and this combination could possibly reduce the cost of production in barley cultivation. According to the experiment conducted in Nigeria, where 2.0 t/ha and 1 t/ha lime were applied, the authors recorded 72% and 48% increases in yield, respectively, over no lime treatments (Buri *et al*., 2005). Workneh *et al*. (2013) also evaluated the effect of ag lime and phosphorus fertilizers on grain yield and the yield components of soybean, and they strongly suggested using a combination of ag lime and phosphorus to achieve the highest yield. It is clear from the results of their study that some amount of the required phosphorus fertilizer could be released from the fixed P by aluminum and magnesium because ag lime improves the availability of phosphorus and reduces its cost by reducing the external application of

phosphorus. The increase in grain yield at an increasing NPSB rate might have resulted from improved root growth, increased uptake of nutrients, and better growth favored due to the synergetic effects of both nutrients, which enhanced yield components and yield. In agreement with this result, Haile *et al*. (2012) found that increasing the N rate from 0 to 120 kg N ha^{-1} increased the grain yield of bread wheat. Bereket *et al. (*2014) also reported that increasing the P rate from 46 to 69 kg P_2O_5 ha^{-1} increased the grain yield of bread wheat by about 6.8%. Similarly, Marschner (2011) reported that the application of nutrients like K, S, Zn, Mg, and B in experiments significantly increased grain yield and yield components of bread wheat as compared to the control (no fertilizer).

3.1.5. Straw yield

The result showed a highly significant (P< 0.05) difference among the main factors of lime and fertilizer rates, but the interaction between the two factors was not significantly different from one another. The treatment that received a large amount of lime (7348 kg/ha) and a large amount of blended NPSB fertilizer (150 kg/ha) had a large amount of straw yield (6225 kg/ha), which is significantly higher compared with the control, which is 1773 kg/ha of straw yield as shown below (Table 2). Similarly, Workneh *et al.* (2013), reported a significant increase in soybean straw yield of 16.3% due to soil liming at a rate of 2.6 t ha^{-1}. The significant increase in straw yield in response to the highest rate of blended NPSB might be attributed to the synergistic roles of nutrients that enhanced the growth and development of the crop. The result is consistent with that of Nasser (2009), who reported an increased straw yield of wheat with an increase in NP fertilizer rates up to 90/45 kg ha^{-1}. Bereket *et al.* (2014) also reported that the highest straw yield was recorded at the highest nitrogen rate of 69 kg N ha^{-1}. Similarly, Gul *et al.* (2012) reported that higher nitrogen application (160 kg ha^{-1}) has a greater contribution to higher straw yield production (9098.65 kg ha^{-1}) compared to control treatment (5302.97 kg ha^{-1}).

3.1.6. Aboveground biomass yield

The above-ground dry biomass yield was significantly affected by the main factors of blended fertilizer, lime, and their interaction ($p < 0.05$). 7348 kg/ha of lime and 150 kg/ha of NPSB fertilizer resulted in the highest amount of total dry biomass of 12165 kg/ha, and the lowest at control was 5108 kg/ha (Table 2). The enhancement of aboveground dry biomass production might be due to integrated nutrient management. Liming improves the soil's physical, chemical, and biological properties. (Dereje and Getachew, 2022) This might have resulted in an adequate supply of micronutrients (N and P) and macronutrients, which could have increased vegetative growth such as the number of branches per plant and leaf area. Thus, the enhanced branching and high leaf area increased the photo interception, which improved dry matter accumulation. In line with this result, (Fageria *et al.,* 2014) reported significantly increased straw and grain yield, resulting in high aboveground biomass of soybeans. Similarly, increased dry matter production of legumes in response to adequate application of fertilizers was reported (Fageria and Baligar, 2008; Veeresh 2003).

According to (Dawit *et al.,* 2015), increasing N from 0 to 184 kg ha-1 and P from 0 to 138 kg ha^{-1} increased the aboveground dry biomass yield of wheat by about 70.1% and 40.6%, respectively. Similarly, (Workineh *et al.,* 2023) reported that the highest biomass yield (11890 kg ha-1) of wheat was observed with 138/115 kg N/P_2O_5 ha^{-1}, while the lowest (9780 kg ha^{-1}) was recorded with 46/46 kg N/P_2O_5 ha^{-1}. Likewise, (Melesse Harfe, 2017) reported

that increasing the N/P fertilizer rate from 46/20 kg N/P_2O_5 ha^{-1} to 69/30 kg N/P2O5 ha^{-1} increased the wheat biomass yield from 10417 kg ha^{-1} to 11233 kg ha^{-1}. In conformity with this result, (Abdulkadir *et al*.,2014;) reported that vegetative growth and biological yield have much dependence on the consumption of chemical fertilizers, and application of the fertilizers led to an increase in the biological yield of wheat. Similarly, (Bekalu and Mamo, 2016) also reported that increasing N rates from 23 to 69 kg ha1 increased the aboveground dry biomass of wheat by about 22.6%.

3.1.7.Harvest index

The harvest index was significantly influenced ($p< 0.05$) by the application of lime and NPSB fertilizer and the interaction of the two factors. The treatment that applied a large amount of lime (7348 kg/ha) and 150 kg/ha of NPSB fertilizer was applied to attain a large amount of harvest index (48.959%) and a small amount of harvest index (46.803%) (Table 2). In conformity with this result, (Shiferaw and Anteneh, 2014), found the application of lime and combinations of fertilizers (NPSB) significantly increased barley yield over the control treatment. Rafat and Sharif (2015), reported that a balanced nutrient supply improves crop yield and thus the harvest index. (Guo *et al.,* 2010) also reported that lime application to acidic soils due to its effect on soil physicochemical properties could result in improved plant nutrition and harvest index. The same, thus the highest harvest index, was obtained with T8: lime (611 kg ha^{-1}) + compost (5 t ha^{-1}) + NPSB (150 kg ha^{-1}) + KCl (100 kg ha^{-1}) + urea (72 kg ha^{-1}) as compared to plots that received applied lime and lower doses of fertilizers. In this study, harvest indices ranged from 37 to 47 and showed an increasing trend with increased combinations of applied lime and organic and inorganic plant nutrient sources. The possible reason could be that the application of lime with an increased rate of compost and inorganic fertilizers might have increased the efficiency of barley in partitioning the dry matter into the reproductive seed sinks (Woubshet *et al.,* 2017).

3.2.Partial budget analysis

The partial budget analysis showed that the highest net benefit of 189,773 Birr ha^{-1} was obtained from the treatment that applied 7348 kg of lime ha^{-1} and 150kg/ha^{-1} of blended NPSB fertilizer (Table 2). However, the lowest net benefit of 101,393.6 ETBha^{-1} was obtained from the control treatment. Therefore, on economic grounds, the application of 7348 kg lime ha^{-1} and 150 kg NPSB ha^{-1} would be the best and most economical for the production of bread wheat in the study area and other areas with similar agroecological conditions.

Table 2. Effect of the interaction of lime and NPSB on straw yield (SY), grain yield (GY), total dry biomass (TDB) and harvest index (HI).

Lime + NPSB kgha^{-1}	SYkgha^{-1}	GY kgha^{-1}	TDBkgha^{-1}	HI (%)
0+0	2597.8^{i}	2383.3^{m}	5108^{l}	46.803^{c}
0+50	2733.2^{hi}	2476.8^{lm}	5210^{kl}	47.584^{bc}
0+100	2615.6^{i}	2566.7^{klm}	5182^{kl}	49.509^{ab}
0+150	2597.8^{i}	2676.7^{jklm}	5275^{kl}	50.737^{a}
1837+0	2832.5^{ghi}	2765.8^{jklm}	5598^{jkl}	49.397^{ab}
1837+50	2905.3^{ghi}	2850.8^{ijkl}	5756^{ijkl}	49.494^{ab}
1837+100	3108.0^{ghi}	2976.1^{ijk}	6084^{ijk}	48.851^{abc}
1837+150	3202.8^{gh}	3082.2^{ij}	6285^{ij}	48.955^{abc}
3674+0	3348.3^{fg}	3241.5^{hi}	6590^{hi}	49.091^{ab}
3674+50	3790.7^{ef}	3667.0^{gh}	7458^{gh}	48.976^{abc}
3674+100	3959.7^{e}	3912.2^{fg}	7872^{fg}	49.695^{ab}
3674+150	4119.9^{de}	4093.3^{efg}	8213^{efg}	9.840^{a}
5511+0	4318.0^{cde}	4182.6^{def}	8501^{def}	49.229^{ab}
5511+50	4635.0^{bcd}	4427.4^{cde}	9062^{cde}	48.869^{abc}
5511+100	4666.9^{bcd}	4442.4^{bcde}	9109^{cde}	48.788^{abc}
5511+150	4639.5^{bcd}	4607.7^{bcd}	9247^{cd}	49.828^{ab}
7348+0	4798.6^{bc}	4636.1^{bc}	9435^{c}	49.191^{ab}
7348+50	4929.3^{b}	4689.4^{bc}	9619^{c}	48.803^{abc}
7348+100	6112.3^{a}	4863.6^{b}	10976^{b}	44.240^{d}
7348+150	6225.0^{a}	5940.0^{a}	12165^{a}	48.959^{abc}
LSD	272.96	94.596	455.51	1.1141
CV	8.54	6.96	7.30	2.79

Means in columns and rows followed by the same letters are not significantly different at 5% level of significance; LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of variation

In line with this result, the total grain yield significantly increased with the application of lime and vermi-compost and attained its maximum value as compared with the control (Table 3). Accordingly, the highest grain yields resulted from the combined application of lime and vermi-compost at 100% lime ha^{-1}+ 2.5 tone vermi-compost ha^{-1}, followed by 75% lime ha^{-1} + 2.5 tone vermi-compost ha^{-1}, even though both were statistically at par. As indicated in Table 3, the highest net benefit was obtained in response to the interaction of 75% lime ha^{-1} with 2.5 tons of vermin-compost ha^{-1} (49,980 birr) (Wegene, 2020). In line with this result, (Bekalu and Mamo, 2016) reported that N application at 69 kg ha^{-1} is effective in attaining a higher grain yield and economic benefit of wheat compared with control in the southern part of Ethiopia. In addition to that, the highest net benefit of ETB (7057.3 ha^{-1}) and marginal rate of return (102.8%) were obtained from the application of 1.88 t lime ha^{-1} along with 23 kg P2O5 ha^{-1} for sorghum production. Therefore, the combined application of 1.88 t of lime ha^{-1} along with 23 kg of P2O5 ha^{-1} for sorghum production is economically feasible (Dereje, 2022).

Table 3: Summary of partial budget and marginal rate of return analysis for response of bread wheat to Lime and blended NPSB fertilizers in Hulbarag District, Southern Ethiopia

Treatments Unadjusted (Kg ha^{-1})				Adjusted Kgha^{-1}		Income (ETB ha^{-1})						
Kgha^{-1}	NPSB ha^{-1}	GY	SY	AGY	SY	Lime (ETB ha^{-1})	Fertilizer (ETB ha^{-1})	Grain (ETB ha^{-1})	Straw (ETB ha^{-1})	FB	TVC	NB MRR (%)
0	0	2200	1773	1980	1595.7	99,000	2393.6	101,393.6	0	101,393.6		
0	50	2476.8	1874	2229	1686.6	111,450	2529.9	113,979.9	8250	105,729.9		D
0	100	2566.7	2615.6	2310	2354	115,500	3531	119,031	10,350	108,681		140.5
0	150	2676.7	2597.8	2409	2338	120,450	3507	123,957	12450	111,507		134.6
1837	0	2765.8	2832.5	2489	2549.3	124,450	3314.1	127,764.1	23,470	104,294.1		D
1837	50	2850.8	2905.3	2566	2614.77	128,300	3922.2	132,222.2	26,620	105,602.2		41.5
1837	100	2976.1	3108	2678	2797.2	133,900	4195.8	138,095	28,720	109,375		179.7
1837	150	3082.2	3202.8	2774	2882.52	138,700	4323.8	143,023	30,820	112,203		134.7
3674	0	3241.5	3348.3	2917	3013.47	145,850	4520.2	150,370.2	41,840	108,530.2		D
3674	50	3667.0	3790.7	3300	3411.63	165,000	5117.4	170,117.4	44,990	125,127.4		526.9
3674	100	3912.2	3959.7	3521	3563.73	176,050	5345.6	181,395.6	47,090	134,305.6		437.1
3674	150	4093.3	4119.9	3684	3707.9	184,200	5561.9	189,761.9	49,190	140,571.9		298.4
5511	0	4182.6	4318	3764	3886.2	188,200	5829.3	194,029.3	60,210	133,819.3		D
5511	50	4427.4	4635	3985	4171.5	199,250	6257.3	205,507.3	63,360	142,147.3		264.4
5511	100	4442.4	4666.9	3998	4200.2	199,900	6300	206,200	65,460	140,740		D
5511	150	4607.7	4639.5	4147	4175.6	207,350	6263.4	213,613.4	67,560	146,053.4		253
7348	0	4636.1	4798.6	4172	4318.7	208,600	6478	215,078	78,580	136,495		D
7348	50	4689.4	4929.3	4220	4436.4	211,000	6654.6	217,654.6	81,730	135,924		D
7348	100	4863.6	6112.3	4377	5501.1	217,200	8251.5	225,451.2	83,830	141,621.2		271.3
7348	150	5940.0	6225	5346	5602.5	267,300	8403.8	275,703.8	85,930	189,773		2,293

Where AGY= adjusted grain yield; SY = Straw yield; GFB = gross field benefit; TVC= total variable costs; NB = net benefit, MRR = marginal rate of return; ETB ha^{-1} = Ethiopian Birr per hectare; D = dominated treatments. Cost of bread wheat seed= 38.00 ETB kg$^{-1;}$ Cost of Lime=10kg^{-1} NPSB= 42 kg^{-1}; Cost of Urea =39 ETB kg $^{-1}$; Labor cost for NPSB application = 7 persons ha^{-1}, each 150 ETB day^{-1}; Labor cost for urea top dress fertilizer application at tillering = 8-person ha^{-1}, each 150 ETB day^{-1}. Market price of bread wheat grain =50 Birr kg ha^{-1} and straw=1.5 Birr kg $^{-1}$ in Hulbarag town at harvesting time in December 2022.

4. Conclusion and Recommendations

The highest number of total tillers (541.67), productive tillers (412.5) per meter square, and number of kernels per spike (90.6) were obtained at the lime rate of 7348kg/ha and NPSB rate of 150 kg ha^{-1}. On the other hand, the lowest number of total tillers (145), number of productive tillers (113.5), and number of kernels per spike (26.112) were recorded at zero level of lime and NPSB rate.

The partial budget analysis revealed that combined applications of 7348kg/ha of lime and 150 kg ha^{-1} blended NPSB fertilizer rate gave higher net benefit of 189,773 Birr ha^{-1} with MRR of 2,293% which is above the acceptable minimum range of MRR 100%, while the lowest net returns (101396.6 ETB $ha^{-1)}$ were recorded with control. Generally, this study provided evidence that yield, and economic returns of bread wheat could be improved by appropriate application of lime and blended NPSB. Therefore, from the result of present study that the application of 7348kg/ha of lime and 150 kg ha^{-1} blended NPSB fertilizer can be tentatively recommended to farmers for production of wheat in the study area and other areas with similar agro-ecology.

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Agronomic and Economic Performances of Cassava (Manihot esculenta crantz) Production through Varieties and Planting Positions in Gena Bosa District of Dawuro Zone, Southwest Ethiopia

Bekalu Abebe Tsige *, Adera Sisay, and Tigist Yisak

Wolita Sodo University, Wolita Sodo, Ethiopia
Corresponding author: bekaluabebe40@gmail.com

Abstract

Limited varieties along with planting position are among the major factors that limit cassava production in Ethiopia. Therefore, a field experiment was conducted to determine the response of cassava varieties to different planting position in the Mela and Bodi sites of Gena Bosa district in Dawro Zone during 2017 cropping season. The treatments consisted of four varieties (Local, Qule, Kello and Awassa-04) and three planting positions (inclined (45°), vertical (90°) and horizontal (180°)). A factorial combination of the two factors was arranged in a Randomized Complete Block Design (RCBD) with three replications. Data was collected on phenology, growth, root yield and yield components. The data collected was subjected to analysis of variance to test the significant effect of the factors involved on response variables. The results indicated that all parameters measured were significantly influenced by the interaction effect of variety and planting position. Slant planting of Kello variety at 45° significantly improved phenology, growth, root morphology, yield components, and root yield of cassava both at Mela and Bodi study sites. The highest mean net benefit (210,544 ETB ha^{-1}) with an acceptable marginal rate of return of 12,493 was obtained from Kello variety planted at 45-degree planting position. Thus, planting Kello variety in slant planting position is suggested for maximizing agronomic and economic returns for cassava farmers.

Keywords: Growth, net benefit, root yield, slant planting

1. Introduction

Cassava **(***Manihot esculenta* crantz) is one of the major root and tuber crops grown in Ethiopia (Amsalu, 2003). It plays a significant role in human food and livestock fodder (Biruk, 2013). It is one of the most widely cultivated crops in lowland areas of Wolaita and Dawro Zones (Kebede *et al*., 2012; Mulualem *et al*., 2013). According to Gena Bosa District Agricultural Development Office (GBDADO) (2017), cassava occupies 56% of the area of land allotted to the production of root and root crops in Gena Bosa district. However, farmers harvest a lower average yield (23.5 t ha^{-1}) than the cassava yields that can be obtained under optimal conditions (80 t ha^{-1}) (Howeler *et al*., 2013; FAO, 2018).

Limited improved varieties and wrong position of planting are some of the serious problems constraining cassava productivity in Ethiopia (Legese *et al*., 2011). Shadrack *et al*. (2017) also indicated that use of low performing varieties and wrong planting position are major yield-limiting factors of cassava. Similarly, Legese *et al*. (2011) reported that limited improved varieties and horizontal position of cassava planting significantly influenced the root yield of cassava at Hawassa, Southern Ethiopia. On the other hand, use of improved varieties of

cassava increased root yield than the local cultivars (Misganaw *et al*., 2020; Mulualem *et al*., 2012).

Planting position has also significant impact on the growth and root yield of cassava (Narmilan and Puvanitha , 2020). About 34% higher root yield of cassava has been obtained in slant planting position than in horizontal planting position (Polthanee *et al.*, 2017). However, in many parts of Ethiopia, horizontal planting position is very common (Legese *et al*., 2011; Legese, 2018; Tadesse *et al*., 2017). Berhanu *et al*. (2023) further reported that limited availability of improved variety is one of the major factors constraining cassava root yield production in Dawuro Zone. Consequently, in most cases, farmers in Dawuro zone plant local cassava cultivar in horizontal position (Berhanu *et al*., 2022; GBDADO, 2017) and get lower cassava root yield. Moreover, the best combination of variety and planting position for cassava is site specific. However, there is limited information on the best combination of variety and planting positions in Gena Bosa district, Dawuro zone. Therefore, this research was conducted to evaluate the combined effects of cassava variety and planting position on the productivity of cassava in Gena Bosa district of Dawuro Zone, Southwestern Ethiopia.

2. Materials and Methods

2.1. Study site description

The study was conducted during the 2017/2018 main cropping seasons on farmers' training center of Mela and Bodi sites of Gena Bosa district of Dawuro Zone, Southwestern Ethiopia. The study site was selected purposively based on its high cassava production potential. The experimental site is located at 07°01'00" N latitude and 37°14'00" E longitude at an altitude of 2355 meters above sea level (Mathewos *et al.,* 2013). In 2017 cropping seasons, the mean monthly temperatures of Mela and Bodi sites ranged from 15°C to 30.5°C and from 14.5 °C to 28.8 °C, respectively with annual rainfall of 1,187 mm and 1376 mm, respectively. The dominant soil type in both study sites is Nitisols (Mathewos *et al.,* 2013).

2.2. Experimental treatments and design

The treatment consisted of four cassava varieties (Local, Qule, Kello and Awassa-04) and three planting positions (45° inclined, vertical (90°) and buried (horizontal) (180°)). The factorial combination of the two factors was laid out in randomized complete block design with three replications. The plot size was 4.5 m x 4.5 m (20.25m^2) with 1 m spacing between plots and 2 m between blocks. The inter-row and intra-row spacing were 90 and 90 cm, respectively, and each row and plot consisted of 6 and 36 plants, respectively. The improved cassava varieties were obtained from Hawassa Agricultural Research Center. These varieties were selected based on their agro-climatic requirements (900–2600 ma.s.l), which suited with the study area (Wondimu *et al*., 2023).

2.3. Experimental management

The experimental field was ploughed three times using a traditional oxen-drawn *Maresha* followed by manual root-bed preparation method and laid out according to the experimental design. The middle part of the main stem that had 25 cm length and at least four buds were used as planting material. In case of slant and vertical planting positions, two-thirds of the length of the cutting buried, whereas in horizontal planting position the

cutting was buried in furrow with depth of 10 cm and fully covered by soil. Planting was carried out on 08 April 2017 following the onset of the rainfall. Weeds were removed by hand weeding after crop emergence up to harvesting. Harvesting was done manually using hand digging tools as done locally by cassava farmers. The crop was harvested on 18 June 2018.

2.4 Data Collection

Phenological data: Data on the number of days to bud sprouting was recorded starting from the date of planting until 50% of the plant population in the plot exhibited visible buds. The number of days to physiological maturity was recorded from the date of planting to when 90% of leaf of the cassava plant stands in a plot changed to a yellow color.

Growth data: Plant height was measured from the base to the tip of the plant by using a measuring tape. The numbers of primary and secondary branches were determined by counting all branches originating from the main stem and primary branches, respectively. The number of buds per plant was recorded by counting the buds sprouted from all stems. Root length was measured from the base to the tip of the longest root by using a measuring tape. The number of roots per plant was counted after the soil clods were carefully removed. Root diameter was recorded by using a digital caliper by attaching it to the center of a stem. All growth data were recorded from five randomly selected plants from the central rows at harvest.

Root Yields: Total root yield, marketable and unmarketable root yield were determined by weighing fresh weight using a sensitive balance at harvest. Marketable root yield (t ha^{-1}) was calculated by weighing all the roots which were free from defects, disease, crack, and other physiological disorders and not underweight per net plot area and converted into tons per hectare. Unmarketable root yield (t ha^{-1}) was calculated by weighing damaged, diseased and insect pest attacked, undersized (<10cm), misshaped, decayed root. Total root yields (t ha^{-1}) were calculated as the sum of the weights of marketable and unmarketable roots from the net plot area and converted into tons per hectare.

2.5. Data Analysis

2.5.1. Analysis of Variance and Mean separation

Homogeneity of variances was checked using the F-test as described by Gomez and Gomez (1984). Since the F-test showed homogeneity of variances for the two study sites for yield and most of the agronomic parameters, a combined analysis of variance was done using SAS version 9.4 (SAS, 2013) following the procedure described by Gomez and Gomez (1984). The treatment means were compared using the Least Significant Difference (LSD) test at 5% level of significance.

2.5.2. Partial budget analysis

Partial budget analysis was done as described by CIMMYT (1988). All costs related to planting materials and labor for planting positions were considered to analyze the partial budget of the cassava. Since root is economic yield for farmers, the partial budget analysis considered the mean marketable root yields of each treatment. Economic analysis was done using the prevailing market prices for inputs at planting and outputs, at the time the crop

was harvested. The costs of planting materials (cuttings) were based on the market price determined by Hawassa Agricultural Research Center, Southern Ethiopia. All costs and benefits were calculated on a hectare basis in Ethiopian Birr (ETB). Total costs that varied (TCV) included the sum of the costs incurred for purchasing of planting materials, transportation, and planting. The price of planting materials for improved varieties was 12 birr/kg while 8 Birr kg–1 for the local variety. The average local market price of cassava root was 8 Ethiopian Birr kg^{-1} in 2018 cropping year. For a hector of land, 300 kg cassava cutting was planted. The labor cost per hectare of land for horizontal, slant and vertical positions were 300 Ethiopian Birr, 200 Ethiopian Birr and 200 Ethiopian Birr, respectively. Actual root yields were adjusted downwards by 10% to reflect the difference between the experimental yield and the yield farmers would expect to get from the same treatment. Then the net benefit (NB) was calculated as the difference between the gross benefit (GB) and the TCV (CIMMYT, 1988). The dominance analysis procedure as described in CIMMYT (1988) was used to select potentially profitable treatments from the range that was tested. The discarded and selected treatments using this technique are referred to as dominated and un-dominated treatments, respectively. The undominated treatments ranked from the lowest to the highest cost. For each pair of ranked treatments, the percentage marginal rate of return (MRR) was calculated. The MRR percentage between any pair of undominated treatments was the return per unit of investment in variety. To obtain an estimate of these returns, the percentage MRR was calculated as changes in net benefit divided by changes in TVC. A treatment, which was non-dominated, and having an MRR greater or equal to 50% and the highest net benefit said to be economically profitable (CIMMYT, 1988). However, in this study MRR of 100% was used to indicate the reality in our country. Thus, for this study, 100% and above return to the investment was considered as a reasonable minimum acceptable rate of return.

3. Results and Discussion

3.1. Crop phenology

3.1.1. Days to flowering

Days to flowering were significantly ($P < 0.05$) influenced by the main and interaction effects of varieties, planting position and location (Table 1). Earlier 50% bud sprouting was observed in vertical planting position in all planted varieties at both locations while delayed bud sprouting was recorded from horizontal planting position. This result shows that horizontal planting position prolonged days to bud sprouting opposed to slant and vertical positions. Overall, the early and late 50% bud sprouting of cassava was obtained from Awassa-04 variety planted in vertical position at Bodi and local variety that planted in horizontal position at Mela, respectively. The result indicated that Awassa-04 variety planted in vertical position at Bodi reduced the number of days to 50% bud sprouting by 23 days compared with local variety that was planted in horizontal position at Mela (Table 1). This may be associated with the exposure to external environments that facilitated early sprouting on vertical planting position than slant and horizontal positions. Since exposure to solar radiation facilitates more bud sprouting of the crops (Howeler *et al*., 2013). In addition, relatively higher temperature at Bodi reduces the days to bud sprouting than Mela (Table 1). This result shows that low temperature delayed bud sprouting, whereas an increased temperature hastened it. The result is consistent with the natural tendency of increased temperature to reduce the days to phonologic parameters of the plants. The result is

consistent with the findings of Misganaw and Bayou (2020) who reported different days to 50% bud sprouting in the same varieties in different locations at Fafen District in Ethiopia.

3.1.2. Days to physiological maturity

Days to physiological maturity of cassava was significantly ($P < 0.05$) influenced by the main and interaction effect of varieties, planting position and location. The number of days required by cassava to reach physiological maturity varied from 400 to 413 days in response to the interaction effect of varieties, planting position and location (Table 1). Numerically the lowest numbers of days to reach physiological maturity were recorded from the local cassava varieties planted in horizontal planting position and Qule variety planted in slant position at Bodi site. On the other hand, the longest days to reach 90% maturity by the plant were recorded from the local cassava variety planted in horizontal position, Qule variety planted in slant position and Kello variety planted in vertical position at Mela site (Table 1). The result is statistically at par with other treatments in both locations (Table 1). The late maturity observed from local variety planted in horizontal planting position at Mela site was due to favorable soil and environmental condition that resulted for delayed maturity in cassava (Sukmadjaja

and Widhiastuti, 2011). The result is in line with the findings of Narmilan and Puvanitha (2020), who reported that interaction of local varieties and horizontal planting position reduced the days to physiological maturity of the cassava by 12 days than local varieties that planted in vertical position.

Table 1. Interaction effect of varieties, planting position and location on days to 50% bud sprouting and days to 90% physiological maturity in southwestern Ethiopia in 2017/2018 cropping season.

Varieties	Planting position	Days to 50% DBS Location		Days to 90% DPM Location	
		Bodi site	Mela site	Bodi site	Mela site
Local	Horizontal (180°)	21.33ab	23.33a	400.00b	413.33a
	Slant (45°)	14.33f	15.67ef	405.33ab	405.67ab
	Vertical (90°)	17.67cde	19.67bc	405.33ab	409.67ab
Qule	Horizontal (180°)	10.33g	11.33g	401.67b	401.33b
	Slant (45°)	21.33ab	23.33a	400.00b	413.33a
	Vertical (90°)	14.33f	15.67ef	403.00b	405.67ab
Kello	Horizontal (180°)	17.67cde	19.67bc	404.67ab	409.67ab
	Slant (45°)	10.67g	11.67g	401.00b	401.67b
	Vertical (90°)	21.33ab	23.33a	405.67ab	413.33a
Awassa-04	Horizontal (180°)	14.33f	15.67ef	401.33b	405.67ab
	Slant (45°)	17.00de	19.00cd	401.33b	409.00ab
	Vertical (90°)	10.33g	11.33g	401.00b	401.33b
LSD (5%			2.09		9.68
CV (%)			3.97		7.6

Means in column and rows followed by the same letter are not statistically significant different at P= 0.05. NS= not significant; DBS= Days to bud sprouting; DPM= Days to physiological maturity ; CV= coefficient of variation; LSD= Least significant difference

3.2. Growth Parameters

3.2.1. Plant height

The height of cassava plants varied significantly ($P < 0.05$) in response to the main and interaction effects of varieties, planting position and location (Table 2). The longest plant height was recorded from local and Qule varieties planted in horizontal and vertical position at Mela, respectively. Planting of local variety with horizontal planting position at Mela resulted in 14.6% more height than Awassa-04 variety planted with slant position at Bodi (Table). The result signifies the vital role of the variety, planting position and location that promote growth of the cassava plants. The result could also be associated with the synergic role of suitable variety, planting position and location combination. It promoted cell division, growth, and differentiation (Narmilan and Puvanitha, 2020). The cumulative role of varieties, planting position and soil nutrients variability in each location attribute for cell division, cell expansion, and enlargement, which might have ultimately contributed to growth in plant height of cassava. Consistent with this result, Polthanee and Wongpichet (2017) reported that slant planting position resulted in 6.6 cm more height than vertical planting position.

3.2.2. Number of buds

The number of buds was significantly ($P \leq 0.01$) affected by main and interaction effect of varieties, planting position and location (Table 2). The highest number of buds was recorded from Kello variety planted with slant position, local variety planted horizontally, and Awassa-04 variety planted with slant position at Mela (Table 2). The Kello variety planted with slant position at Mela resulted in about 48.2% larger number of buds than local variety at Bodi. The result might be associated with the combined role of varieties, planting position and location. The effect of location is more significant compared to the other factors involved in the trial.

3.2.3. Number of primary branches per plant

The number of primary branches per plant responded significantly ($P < 0.01$) to the main and interaction effects of varieties, planting position and location (Table 2). The highest number of primary branches per plant was obtained from Kello variety planted in slant position at Mela, which is statically similar with local variety planted in horizontal position and Awassa-04 variety planted in vertical position at Mela. The results were statically at par with local variety planted in horizontal position and Kello variety planted in slant position at Bodi (Table 2). The results of this study indicated that variety, planting position and location alone would not lead to the maximum number of primary branches per plant. However, the interaction of variety, planting position and location led to a significantly higher number of primary branches per plant. Since, the soil nutrient content varies from location to location and plants that received sufficient nutrient typically exhibit vigorous plant growth that is attributed to the number of the branch (Sukmadjaja and Widhiastuti, 2011). On the other hand, the number of primary branches varied as per the variety planted. Whereas the combination of suitable planting position with appropriate variety facilitates healthy growth and increased the number of branches per plant (Polthanee and Wongpichet, 2017). In line with this result, Shadrack *et al*. (2017) indicated interaction of variety, planting position and location highly influenced the number of branches per plant of cassava.

Table 2. Interaction effects of varieties, planting position and location on growth parameters of cassava in Gena Bosa district, Southwestern Ethiopia in 2017/2018 cropping seasons.

Varieties	Planting position	PH		NB		NPB		NSB	
		Location		Location		Location		Location	
		Bodi site	Mela site	Bodi site	Mela site	Bodi site	Mela site	Bodi site	Mela site
Local	Horizontal (180°)	260.67d	284.13a	24.00i	26.00i	2.33d	2.67d	4.67c	5.67c
	Slant (45°)	253.00e	275.80bc	34.33h	36.33fhg	3.33cd	4.33cd	6.67 bc	8.00bc
	Vertical (90°)	248.67e	271.03bc	38.66efg	41.67bcd	4.67cd	5.67c	9.33bc	11.33b
Qule	Horizontal (180°)	251.67e	271.03bc	43.33b	46.33a	9.00ab	11.00ab	18.00a	21.33a
	Slant (45°)	260.00d	273.60bc	23.66i	25.67i	3.00d	4.00cd	6.00c	7.00bc
	Vertical (90°)	260.67d	284.13a	24.33i	35.67h	3.33cd	4.33cd	5.33c	8.00bc
Kello	Horizontal (180°)	248.67e	271.03bc	39.00def	42.00bc	4.67cd	5.67c	9.33bc	11.33b
	Slant (45°)	251.00e	273.60bc	43.33b	46.33a	9.33ab	11.33a	18.67a	22.00a
	Vertical (90°)	260.67d	251.67e	33.67h	26.33i	2.67d	3.33cd	5.33c	6.33c
Awassa-04	Horizontal (180°)	253.67e	276.53b	34.00h	36.00gh	3.33cd	4.33cd	6.67bc	8.00bc
	Slant (45°)	248.00e	270.30c	39.33cde	42.33b	4.67cd	5.67c	9.33bc	11.33b
	Vertical (90°)	251.67e	274.33bc	43.33b	46.33a	8.67b	10.67ab	17.33a	20.67a
LSD (5%		5.83		2.79		2.34		4.86	
CV (%)		6.9		2.43		13.49		14.29	

Means in column and rows followed by the same letter are not significantly different at P = 0.05 ; PH = Plant height, NB=number of buds, NPB=number of primary branches, NSB= number of secondary branches

3.2.4. Number of secondary branches per plant

The number of secondary branches per plant responded significantly ($P < 0.01$) to the main and interaction effects of varieties, planting position and location (Table 2). The highest number of secondary branches per plant was obtained from Kello variety planted in slant position at Mela, which is statically similar with local variety planted in horizontal position and Awassa-04 variety planted in vertical position at Mela. The results were statically at par with local variety planted in horizontal position and Kello variety planted in slant position at Bodi (Table 2).

3.3. Root Morphology of Cassava

3.3.1. Root length

The main and interaction effect of varieties, planting position and location significantly ($P < 0.05$) influenced the root length. The root length might be associated with variety, planting position and availability of sufficient nutrients in each location. For instance, maximum root length was produced in response to local variety planted in slant position at Bodi which is statically similar with the same variety planted in horizontal position at Mela and Kello variety planted in slant position at Mela (Table 3). The maximum root length achieved from that treatment might be due to maximum vegetative growth in local variety due to adaptability to environment and in which the root length increased to balance root to shoot ratio (Dolan and Davies, 2014). Also, the slant planting position and the soil textural class at Bodi might contribute to root perforation and elongation. In line with this finding, Wondimu *et al.* (2023) reported the tallest root length on local cultivar than improved varieties at Southwestern Ethiopia.

Table 3. Interaction effects of varieties, planting position and location on root morphologic parameters of cassava in Gena Bosa district, Southwestern Ethiopia in 2017/2018 cropping seasons

Varieties	Planting position	Root length		Root diameter		Number of roots per plant	
		Location		Location		Location	
		Bodi site	Mela site	Bodi site	Mela site	Bodi site	Mela site
Local	Horizontal (180°)	43.33k	46.80k	2.00j	3.00ij	2.67j	2.67j
	Slant (45°)	121.00a	98.67fg	4.33f-i	5.67fgh	6.00fgh	7.00ef
	Vertical (90°)	99.67fg	107.63de	4.66f-h	6.33def	5.33f-i	6.33efg
Qule	Horizontal (180°)	110.00cd	118.80ab	8.33cd	10.67b	11.67cd	13.33c
	Slant (45°)	55.33j	59.73j	3.00ij	4.00g-j	3.67ij	4.33hij
	Vertical (90°)	87.33i	46.07k	2.00j	3.67hij	4.67ghi	5.67fgh
Kello	Horizontal (180°)	99.67fg	107.63de	4.67g-i	6.33def	5.67fgh	6.67ef
	Slant (45°)	114.00bc	123.10a	10.33bc	13.33a	15.33b	17.33a
	Vertical (90°)	42.67k	46.07k	2.00j	3.00ij	2.67j	2.67j
Awassa-04	Horizontal (180°)	87.33i	94.30gh	2.67ij	3.67hij	4.33hij	5.33f-h
	Slant (45°)	102.33ef	110.53cd	6.00efg	8.00de	7.00ef	8.00e
	Vertical (90°)	112.00cd	94.30gh	8.33cd	10.67b	11.00d	12.00cd
LSD (5%)		5.85		2.19		1.81	
CV (%)		2.05		12.12		8.06	

Means in column and rows followed by the same letter are not significantly different at P = 0.05

3.3.2.Root diameter

The root diameter was significantly ($P < 0.01$) affected by the main and interaction effect of varieties, planting position and location. The widest root diameter was recorded in Kello variety in slant planting position at Mela (Table 3). Kello variety planted in slant position at Mela was 56.7% higher root diameter than that of local variety in horizontal planting position at Bodi (Table 3). The results clearly show that the cumulative effect of varieties, planting position and location has high effect on root diameter. The root diameter directly associates with the variety, the soil fertility status of planted location and proper planting position. Particularly nutrient deficiency promotes the production of more roots per plant as an adaptation mechanism to low nutrient supply (Fageria *et al*., 2011). This suggestion is consistent with the proposition of Legesse (2018) who reported that interaction effect of varieties, planting position and location has a significant influence on the diameter of cassava at Amaro, southern Ethiopia.

3.3.3. Number of roots per plant

The main and interaction effect of varieties, planting position and location significantly ($P < 0.05$) influenced the number of roots per plant. There is no discernable trend observed in the number of roots per plant in the response to varieties, planting position and location (Table 3). The highest root number was recorded from Kello variety with slant planting position at Mela. This result indicate that 15 more roots were produced per plant than local variety planted with horizontal position at Bodi and Mela (Table 3). This result may indicate the cumulative effect of genetic potential of Kello variety and suitability of slant position that enhanced the number of roots per plant at Mela. The number of roots per plant directly correlated with planted cassava variety (Wondimu *et al.,*2023) and planting position (Polthanee and Wongpichet, 2017). Also fertile soil promotes the number of roots per plant (Fageria *et al*., 2011).Furthermore, some studies conducted in a different part of Ethiopia had shown the positive effects of varieties, planting position and location to increase the number of roots per plant of cassava (Legese *etal*., 2011; Misganaw and Bayou, 2020; Mulualem and Ayenew, 2012; Mulualem and Dagne, 2015). Overall, this study noted that the cumulative effect of improved varieties, suitable planting position and the soil fertility status of planned location has an impact on the number of roots per plant of cassava.

3.4. Root Yield

3.4.1. Unmarketable root yield

The main and interaction effects of varieties, planting position and location significantly ($P<0.01$) influenced unmarketable roots (Table 4). The highest unmarketable root yield was observed in the local variety planted in horizontal position at Bodi and Mela and Qule variety planted vertically at Bodi (Table 4). The result clearly indicates that Kello variety is not significantly influenced by the planting position (Table 4.). Unmarketable roots obtained from local variety planted horizontally at Bodi exceeded those from Awassa-04 variety planted at a slant position at both Bodi and Mela by 72.8%. This indicates that the local variety, in fact, had many defects and planting of improved varieties with proper planting position are required to reduce the amount of unmarketable root production. Similar results were reported by Wondimu *et al*. (2023), who found higher proportion of unmarketable roots in local cassava cultivar.

3.4.2. Marketable roots

The marketable root yield was significantly ($P < 0.01$) influenced by the main and interaction effect of varieties, planting position and location (Table 4). The marketable root yield was higher in all improved varieties compared to the local cultivar in both location and across all planting positions (Table 4). The highest marketable root yield was recorded for Kello variety planted in the slant position at Mela, which was 64.6% higher than that of the local cultivar planted in horizontal position at Mela (Table 4). The highest marketable root yield from the treatment was statistical similar to that of Awassa-04 variety planted in vertical position at Mela (Table 4). These results indicate that combining improved varieties with the appropriate planting position and location resulted in higher marketable root yield. In agreement with these results, Sukmadjaja and Widhiastuti (2011) reported significantly higher marketable root yields in response to the slant planting position.

3.4.3. Total root yield

The total root yield was significantly ($P < 0.01$) influenced by the main and interaction effect of varieties, planting position and location (Table 4). The improved varieties significantly and consistently increased total root yield of cassava compared to local cultivar in three planting positions at both locations (Table 4). Accordingly, highest total root yield was obtained from Kello variety planted in slant position at Mela, which is statistical at par with local variety planted horizontally and Awassa-04 variety planted vertically at Mela (Table 4). The improved cassava variety planted at proper position and location likely experienced higher photosynthesis rates and exhibited vigorous plant growth contributing to increased total root yield (Sukmadjaja and Widhiastuti, 2011). Overall, the enhanced total root yield in cassava due to improved varieties and proper planting position can be attributed to their physiological roles in plant growth and total root yield. This implies that the right combination of improved cassava variety with proper planting position at favorable place fulfilled the growth requirements of the plants through synergic effects (Narmilan and Puvanitha, 2020). Consistent with these findings, Polthanee and Wongpichet (2017) reported planting improved variety in slant position increased the total root yield of cassava by 34.7% compared to local cultivar planted horizontally. Similarly, Legese *et al* (2011) also showed a 111% improvement in total root yield of cassava due to planting Kello and Qule varieties in slant position.

2.5. Partial budget analysis

The maximum net benefit of 210,520 ETB ha^{-1} was recorded for Kello variety planted in slant position at Mela site followed by Awassa-04 variety planted vertically (197,560 ETB ha^{-1}**)**. However, the minimum net benefit of 66,900 ETB ha^{-1} and 73,140 ETB ha^{-1} was obtained from the local cultivar planted horizontally at both Bodi and Mela site respectively. Overall, the economic analysis revealed the highest net benefit (210,520 ETB ha^{-1}) with an acceptable marginal rate of return (MRR) of 12,489.09 for Kello variety planted in slant position at Mela site. The economical net gain from Kello variety planted in slant position at Mela site was about 2.28 times higher than that of the local cultivar planted horizontally at Bodi site (Table 5). The highest economical net gain obtained from Kello variety planted in slant position at Mela site could be attributed to the increased economic yield resulting from the optimal combination of variety, planting position and location, which maximizes net profit. Therefore, planting Kello variety in slant position is recommended for cassava farmers in the study area to achieve higher net benefit.

Table 4. Interaction effects of varieties, planting position and location on root unmarketable, marketable and total yield of cassava in Gena Bosa district, Southwestern Ethiopia in 2018 cropping seasons

Varieties	Planting position	Unmarketable yield (t ha^{-1}) Location		Marketable yield(t ha^{-1}) Location		Total root yield(t ha^{-1}) Location	
		Bodi site	Mela site	Bodi site	Mela site	Bodi site	Mela site
Local	Horizontal (180°)	3.67a	3.50ab	9.67k	10.53jk	13.33f	14.02f
	Slant (45°)	1.00ef	1.00ef	19.00fgh	20.70ef	20.00e	21.66de
	Vertical (90°)	1.67c-f	1.60c-f	18.67gh	20.33efg	20.33e	21.93de
Qule	Horizontal (180°)	1.00ef	1.00ef	25.33d	27.63bc	26.33c	28.56abc
	Slant (45°)	1.67c-f	1.60c-f	12.00ij	13.10j	13.67f	14.66f
	Vertical (90°)	2.33a-e	2.23a-e	17.67h	19.23fgh	20.00e	21.47de
Kello	Horizontal (180°)	1.67c-f	1.60c-f	18.67gh	20.33efg	20.33e	21.93de
	Slant (45°)	0.67f	2.90abc	27.33bc	29.77a	28.00abc	30.43a
	Vertical (90°)	3.00abc	1.60c-f	9.33k	10.17jk	12.33f	13.02f
Awassa-04	Horizontal (180°)	2.67a-d	2.57a-d	17.67h	19.23fgh	20.33e	21.79de
	Slant (45°)	1.00ef	1.00ef	20.33fgh	22.17e	21.33de	23.11d
	Vertical (90°)	1.33def	1.30def	25.67cd	27.97ab	27.00bc	29.24ab
LSD (5%)		1.42		1.97		2.45	
CV (%)		25.34		3.25		3.69	

Means in column and rows followed by the same letter are not significantly different at P = 0.05

Table 5. Partial budget analysis of cassava influenced by varieties and planting position in Gena Bosa district, Southwestern Ethiopia in 2018 cropping seasons.

Varieties	Planting position	UMY(t ha^{-1})		AMY(t ha^{-1})		TGB (ETB ha^{-1})		VC(ETB ha^{-1})		NB(ETB ha^{-1})		MRR (%)	
		Bodi	Mela	Bodi	Mela	Bodi	Mela	Bodi	Mela	Bodi	Mela	Bodi	Mela
Local	Horizontal	9.67	10.53	8.70	9.48	69,600	75,840	2,700	2,700	66,900	73,140		
	Slant	19.00	20.70	17.10	18.63	136,800	149,040	2,600	2,600	134,200	146,440	D	D
	Vertical	18.67	20.33	16.80	18.30	134,400	146,400	2,600	2,600	131,800	143,800	D	D
Qule	Horizontal	25.33	27.63	22.80	24.87	182,400	198,960	3,900	3,900	178,500	195,060	10160	10160
	Slant	12.00	13.10	10.80	11.79	86,400	94,320	3,800	3,800	82,600	90,520	1580	1580
	Vertical	17.67	19.23	15.90	17.31	127,200	138,480	3,800	3,800	123,400	134,680	5594.545	5594.545
Kello	Horizontal	18.67	20.33	16.80	18.30	134,400	146,400	3,900	3,900	130,500	142,500	5780	5780
	Slant	27.33	29.77	24.60	26.79	196,800	214,320	3,800	3,800	193,000	210,520	12489.09	12489.09
	Vertical	9.33	10.17	8.40	9.15	67,200	73,200	3,800	3,800	63,400	69,400	D	D
Awassa-04	Horizontal	17.67	19.23	15.90	17.31	127,200	138,480	3,900	3,900	123,300	134,580	5120	5120
	Slant	20.33	22.17	18.30	19.95	146,400	159,600	3,800	3,800	142,600	155,800	7514.545	7514.545
	Vertical	25.67	27.97	23.10	25.17	184,800	201,360	3,800	3,800	181,000	197,560	11310.91	11310.91

UMY = Unadjusted marketable yield; AMY = adjusted marketable yield; TGB = Total gross benefit; VC = Variable cost; NB = Net benefit; MRR= Marginal rate of return, ETB ha^{-1} = Ethiopian birr per hectare; D= dominated treatment

3. Conclusion and Recommendations

The results of this study demonstrated that maximum total cassava root yield of 30.43t ha^{-1} was recorded for Kello variety planted in slant position at Mela site. The result was statistically at par with the root yield obtained in Awassa-04 variety planted vertically at Mela site. So, where there is no Kello variety farmers can use Awassa-04 variety with vertical planting as second option. Overall, the root yield from Kello variety planted in slant position at Mela site was nearly twice as that of the local cassava planted horizontally at Bodi site. For optimal root yield (30.43 t ha^{-1}) and the highest mean net benefit (210,520 ETB ha^{-1}) with an acceptable marginal rate of return (12,489.09%), farmers in the study area are advised to cultivate Kello variety in slant planting position. Therefore, these findings suggest that planting Kello variety in slant position can maximize both agronomic and economic returns, enhancing food security, increasing income, and improving the livelihoods of cassava farmers in the study area, and areas with similar agroecology.

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The Combined Use of Agricultural Lime and Vermicompost for Soil Acidity Amendment and Improved Barley Production in the Central Highlands of Ethiopia

Derib Kifle*, Yohanis H/Yesus, Getahun Dereje and Fikadu Mosisa

Ethiopian Institute of Agricultural Research, Holeta Agricultural Research Center, P.O. Box 31, Ethiopia
*Corresponding author E-mail: deraltes2009@gmail.com,

Abstract

Soil fertility decline, caused by factors such as soil acidity, topsoil erosion, organic matter depletion, poor soil structure, and salinity, poses a major challenge to sustainable crop production in Ethiopia. Integrated soil fertility management that combines organic and inorganic inputs is therefore essential. A three-year on-station experiment (2019–2021) was conducted at Damotu Farmers Training Center (FTC) to evaluate the effects of lime and vermicompost, applied alone and in combination with NP fertilizer, on barley productivity and soil chemical properties. The experiment was arranged in a randomized complete block design (RCBD) with three replications, testing different application rates of lime, vermicompost, and NP fertilizer. Three-year mean results showed that the highest dry biomass yield (11.15 t ha^{-1}) and grain yield (5.35 t ha^{-1}) were obtained from the combined application of recommended rates of vermicompost and lime with 50% of the recommended NP fertilizer. However, the economically optimum grain yield (5.05 t ha^{-1}) was achieved with 50% recommended vermicompost and 50% recommended lime (2.3 t ha^{-1} vermicompost and 1.3 t ha^{-1} lime) combined with half the recommended NP fertilizer, resulting in a 156.3% yield increase over the control. Soil analysis revealed that soil pH increased from 4.43 to 6.08, while exchangeable acidity declined from 1.70 to 0.189 cmol kg^{-1} under the application of 4.6 t ha^{-1} vermicompost and 2.6 t ha^{-1} lime without NP fertilizer. The same treatment also recorded the highest total nitrogen (0.198%) and available phosphorus (19.68 ppm). The study demonstrates that integrating lime and vermicompost with reduced NP fertilizer rates effectively enhances barley yield, while optimal organic and lime application improves soil chemical properties in acidic soils.

Keywords: Exchangeable acidity, grain yield response, Integrated soil fertility, Nutrient enhancement, soil chemical properties.

1. Introduction

Ethiopia faces persistent challenges related to soil fertility degradation, which cannot be effectively addressed through the sole application of chemical fertilizers the dominant soil fertility management practice to date. Major constraints contributing to soil fertility decline include severe topsoil erosion, soil acidity, depletion of soil organic matter due to extensive biomass removal for fuel, deficiencies of both macro- and micro-nutrients, deterioration of soil physical properties, and soil salinity (Menale *et al*., 2011). These interrelated problems have resulted in declining agricultural productivity and threaten the sustainability of crop production systems, underscoring the need for integrated and sustainable soil management strategies.

Among these constraints, soil acidity represents one of the most critical limitations to crop production in the Ethiopian highlands. Acidic soils are characterized by nutrient imbalances and elemental toxicities, particularly from aluminum (Al) and manganese (Mn), which severely restrict root growth, nutrient uptake, and overall crop performance. To mitigate soil acidity and its adverse effects, both organic and inorganic soil amendments have been widely investigated. Organic matter plays a vital role in acid soil remediation by forming stable complexes with toxic aluminum ions, thereby reducing their solubility and bioavailability (Stevenson, 1994). During the decomposition of plant and animal residues, microorganisms release or synthesize various organic compounds capable of strongly binding aluminum, thus minimizing its toxicity to plants (Okpara, 2007).

Humic substances, which are rich in oxygen-containing functional groups such as carboxyl (–COOH), phenolic (–OH), and carbonyl (C=O), exhibit a high affinity for polyvalent metal ions. These functional groups promote aluminum immobilization through mechanisms such as chelation, adsorption, and co-precipitation (Haynes, 1984). Consequently, aluminum toxicity is substantially reduced when Al is complexed with high-molecular-weight organic compounds (Peter, 2011).

Lime application remains the most widely recognized and effective inorganic strategy for ameliorating soil acidity. Liming is globally accepted as a standard practice for improving acidic soils by neutralizing excess hydrogen ions and reducing exchangeable aluminum toxicity (Munroe & Murdock, 1993). The primary function of lime is to raise soil pH, thereby alleviating Al and Mn toxicity while supplying essential base cations such as calcium (Ca) and magnesium (Mg). Increasing soil pH above 5.5 through lime application has been shown to significantly decrease harmful levels of soluble and exchangeable aluminum. Furthermore, studies indicate that combining lime with organic amendments enhances soil chemical stability, improves nutrient availability, and sustains crop productivity more effectively than either amendment applied alone (Opala, 2011).

Despite the proven benefits of liming and organic amendments such as vermicompost, their use in Ethiopia has not been sufficiently guided by site-specific research tailored to local soil conditions and crop requirements. Consequently, the potential of these amendments to improve soil fertility and crop yields under Ethiopian agro-ecologies remains inadequately explored. Therefore, the present study aims to evaluate the individual and combined effects of vermicompost and lime on soil acidity amelioration, crop productivity, and selected soil chemical properties of acidic soils. By integrating organic and inorganic soil amendments, this research seeks to contribute to sustainable soil fertility management and enhanced agricultural productivity in Ethiopia.

2. Materials and Methods

2.1. Study area

The experiment was conducted at the Farmers Training Center (FTC) in Damotu Kebele, Ejere district, as a permanent plot study.

2.2. Experimental Procedure

A composite soil sample was collected from the surface layer (20 cm) of the entire experimental field before treatment application. Post-harvest soil samples were collected from each treatment plot at the same depth to assess major soil properties and examine the residual effects of organic and inorganic soil acidity amendments.

2.3. Soil Laboratory Analysis

Soil chemical properties were analyzed following standard laboratory procedures. Soil pH was measured potentiometrically using a pH meter with a combined glass electrode in a 1:2.5 soil-to-water ratio (Brady and Weil, 1996). Exchangeable acidity was determined using the base titration method, involving soil saturation with 1M KCl solution followed by titration with sodium hydroxide (Rowell, 1994). Organic carbon was analyzed using the wet oxidation method (Walkley and Black, 1934), while total nitrogen (N) was determined using the Kjeldahl method (Jackson, 1967). Available phosphorus (P) was extracted using the Bray II method (Bray and Kurtz, 1945) and quantified spectrophotometrically.

2.4. Lime and Vermicompost Application

The soil amendments used were vermicompost (VC) and ground limestone. The lime requirement was calculated based on soil exchangeable acidity and bulk density at a depth of 0.15 m, following Kamprath's method. Vermicompost application rates were estimated based on nitrogen equivalency. Both amendments were incorporated into well-prepared plots one month before planting, mixed thoroughly into the plow layer. The test crop used was an early-maturing barley variety, BH-1307.

2.5. Treatment and Experimental Design

The experiment consisted of nine treatments with different combinations of lime, vermicompost, and NP fertilizer rates. These treatments were arranged in a randomized complete block design (RCBD) with three replications.

Treatment description

1. Control/No amendment
2. Rec. VC + rec. NP
3. Rec. lime + rec. NP
4. Rec. VC + rec. Lime + 50% rec. NP
5. 50% rec.VC + rec. Lime + rec. NP
6. Rec.VC + 50% rec. lime + rec. NP
7. 50% rec.VC + 50% rec. lime + rec. NP
8. 50 % rec. VC + 50 % rec. lime + 50 % rec. NP
9. Rec. VC + rec. lime

2.6. Data Collection and Analysis

Agronomic data, including plant height and spike length, were recorded from ten randomly selected plants in the middle rows of each plot at harvest. Biomass and grain yield were measured from the central rows. Soil and crop data were managed using Microsoft Excel and analyzed using the General Linear Model procedure in SAS (SAS Institute, Cary, 2000).

Treatment means were compared using the Least Significant Difference (LSD) test at a 5% significance level.

3. Results and Discussion

3.1. Selected Soil Properties before Treatment Application

The initial soil analysis results before treatment application are presented in Table 1. The soil of the study area was classified as sandy clay loam in texture (Jones, 1983) and was rated as very strongly acidic based on the classification by Tekalign *et al*. (1991). The soil had a low available phosphorus (P) content, likely attributed to its high P-fixing capacity.

Table 1. Selected soil properties of the study area

Parameter	Test Result
pH H2O (1:2.5)	4.29
Available phosphorus (ppm)	8.52
Organic carbon (%)	1.5
Sand (%)	48.3
Clay (%)	36.4
Silt (%)	15.4
Textural Class	Sandy clay loam
Bulk density (g/cm^3)	1.28
Exchangeable acidity (cmol/kg soil)	1.7

3.2. Chemical Composition of the Vermicompost Product

The vermicompost was produced using crop residues of maize and soybean, cow dung, and topsoil, with red earthworm (*Eisenia fetida*). The chemical composition of the vermicompost is presented in Table 2. The nitrogen (N) and phosphorus (P) contents were 1.51% and 0.9%, respectively, which were higher compared to the untreated soil (Daryl, 1983). The vermicompost had a moderate alkaline pH (8.07) and an organic carbon content of 19.67%, with a low C:N ratio of 13.73. The low C:N ratio suggests a high potential for mineralization, enhancing the availability of N and P in the soil for plant uptake. Enwenzo (1979) demonstrated that nitrogen mineralization increases with decreasing C:N ratio, indicating that organic materials with lower C:N ratios release more nitrogen into the composting medium, thereby enhancing nutrient availability for plants.

Table 2. Selected chemical properties of the vermicompost utilized in the experiment

Parameters	Value
pH (1:2.5H_2O)	8.07
OC (%)	19.64
TN (%)	1.43
C:N	13.73
P (%)	0.9
EC (mS cm^{-1})	3.12

P^H = Power of hydrogen activity; C= Carbon; N = Nitrogen; P = Phosphorus and EC= Electrical conductivity.

3.3. Characterization, rating and application of liming materials

The liming material was obtained from Midrok limestone crushing factory and was characterized in terms of its cation content, Calcium carbonate equivalent (*CCE*) and Moisture factor (*mf*). Lime requirement was calculated based up on soil exchangeable acidity, employing lime rate estimation technique developed by Kamprath (1984).

Table 3. Characteristic properties of agricultural lime.

Lime type	$CaCO_3$ equiv. (%)	Moisture (%)	Exchangeable cations (%)			
			Ca	Mg	K	Na
Calcite lime	93.68	0.0647	2.9185	0.0003	0.0018	0.0007

3.4. Effects of Lime and Vermicompost on Barley Yield and Yield Components

The study found that spike length was significantly influenced by the combined use of lime and vermicompost, resulting in a greater spike length than the control (Figure 1). Similarly, grain yield was significantly higher when both amendments were used together compared to their individual applications. Total biomass yield was also significantly affected ($p<0.05$) by the combination of lime and vermicompost (Figure 1). The highest total biomass (11.15 t ha^{-1}) was achieved with the application of recommended vermicompost and recommended lime along with 50% recommended NP fertilizers, whereas the lowest (6.72 t ha^{-1}) was recorded in the control. The increase in biomass due to liming is attributed to reduced soil acidity (lower H^+ and Al^{3+} levels) and improved nutrient availability, particularly Ca and P.

Previous studies support these findings. For Example, Achalu *et al*. (2012) reported that integrating lime and vermicompost on acidic soils significantly increased barley biomass. Likewise, Tesfaye Burju (2018) found that combining organic and inorganic fertilizers had a highly significant effect ($p<0.01$) on total biomass in food barley.

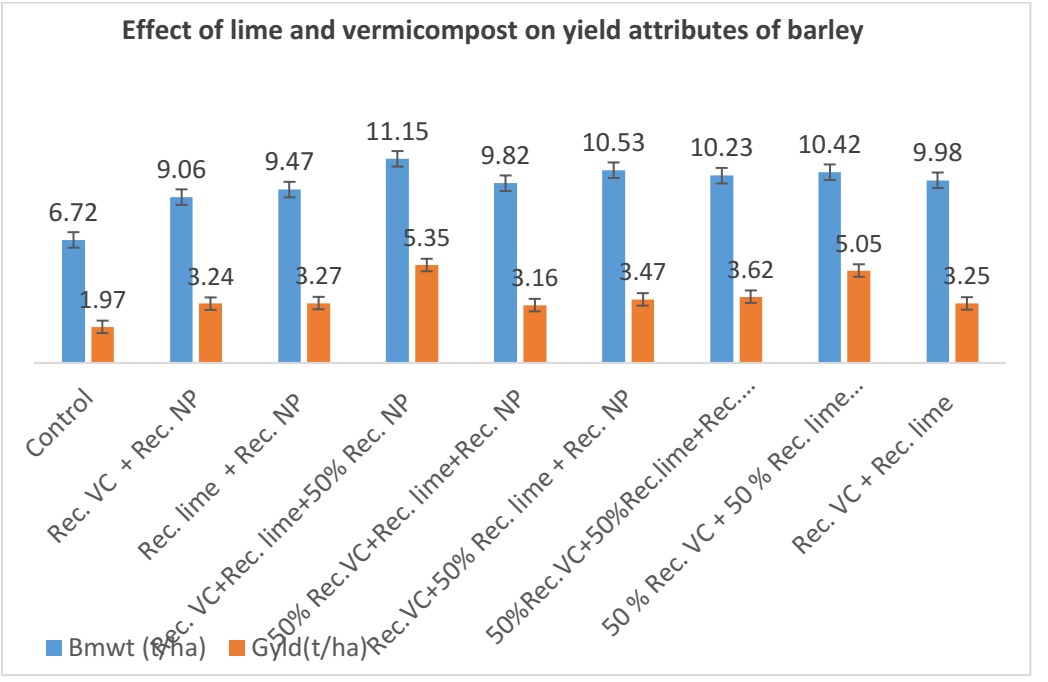

Figure 1. Yield performance of barley under different treatments

The highest dry biomass yield (11.15 t/ha) and the maximum grain yield (5.35 t/ha) were obtained from the application of recommended vermicompost (rec.VC) and recommended lime, along with 50% recommended NP fertilizer. However, economically optimum grain yield (5.05 t/ha) was achieved with a combination of 50% rec.VC and 50% rec. lime (equivalent to 2.3 t/ha vermicompost and 1.3 t/ha lime) along with half dose of recommended NP fertilizer. This treatment resulted in a yield increase of over 150%, providing a grain yield advantage of 156.3% compared to the control, and 45.43% and 55.8% higher yields than the sole lime and sole vermicompost treatments, respectively (Figure 1).

The significant improvement in grain yield can be attributed to the synergistic effects of lime and vermicompost. The combined application of lime and vermicompost effectively increased soil pH, reduced exchangeable acidity by neutralizing toxic aluminum (Al^{3+}) and hydrogen (H^{+}) ions, and enhanced overall barley crop performance. Additionally, an interaction between organic matter and polyvalent metal ions, such as aluminum, likely influenced the solubility and availability of essential plant nutrients such as TN and Av.P. This process contributed to improved soil fertility by increasing exchangeable base status and optimizing nutrient uptake by the crop.

The beneficial impact of lime on yield can be linked to its role in neutralizing soil acidity, reducing aluminum toxicity, supplying calcium (Ca^{2+}), and improving the availability of vital nutrients. Moreover, lime application enhances soil chemical, physical, and microbial properties, creating a more favorable environment for root growth and microbial activity, which further supports plant productivity (Achalu *et al*., 2012).

3.5. Soil Properties after Harvest

The soil test results indicated that soils amended with lime and vermicompost have a higher pH (6.08) and lower exchangeable acidity (0.189 meq/100g soil) than non-amended soil (Table 3). The increase in soil pH and the reduction in exchangeable acidity due to lime and vermicompost application may be partly attributed to the replacement of H^+ and Al^{3+} ions on clay surfaces with Ca from lime, which neutralizes soil acidity (Figure 2). Another probable reason for the increase in soil pH and decrease in exchangeable acidity is the alkaline nature of vermicompost, which contributes to an increase in basic cations.

Table 4. Soil chemical properties as affected by the integrated use of lime and vermicompost

Test parameters	**pH** (1:2.5H2O)	**Ex.A** (cmol/kg soil)	**OC (%)**	**TN (%)**	**Av. P(ppm)**
Control/No amendment/	4.43	1.7^{a}	1.02	0.11^{b}	9.76^{b}
Rec. VC + rec. NP	5.49^{d}	0.483^{a-c}	1.89	0.182^{ab}	17.29^{ab}
Rec. lime + rec. NP	5.99^{a}	0.197^{c}	1.88	0.182^{ab}	18.21^{ab}
Rec. VC + rec. lime+50% rec . NP	6.03^{a}	0.245^{bc}	1.90	0.198^{a}	19.68^{ab}
50% Rec.VC + rec. lime + rec. NP	5.95^{ab}	0.352^{a-c}	1.94	0.179^{ab}	17.65^{ab}
Rec.VC+50% rec. lime + rec. NP	5.76^{bc}	0.314^{a-c}	1.95	0.183^{ab}	19.41^{ab}
50%Rec.VC+50%rec. lime+rec. NP	5.62^{cd}	0.373^{a-c}	1.86	0.186^{a}	18.61^{a}
50 % (Rec. VC + rec. lime + rec. NP)	5.72^{c}	0.388^{a-c}	1.97	0.182^{ab}	$17.9a^{b}$
Rec. VC + rec. lime	6.08^{a}	0.189^{c}	1.96	0.180ab	18.61^{ab}
CV	3.65	84.9	7.09	5.11	19.63
LSD	0.198	0.189	NS	0.008	3.44

Where: Ex A=exchangeable acidity, OC=Organic carbon, TN=Total Nitrogen and Av P=available Phosphorus

Vermicompost raises soil pH due to its high content of basic cations and buffering capacity, which enhances nutrient availability, particularly phosphorus, while reducing toxic elements such as Al, Mn, and Fe. According to Getachew *et al*. (2017), lime application raises soil pH to levels optimal for barley growth while significantly reducing exchangeable Al^{3+} to a minimum level of 0.1 cmol (+) kg^{-1}. This reduction enhances phosphorus availability due to increased pH and decreased acidity. Similarly, Abdissa *et al*. (2018) reported that lime application, either alone or in combination with vermicompost, significantly increased soil pH. Their study found the highest soil pH values from the combined application of lime at 4 t ha^{-1} and vermicompost at 5 t ha^{-1}.

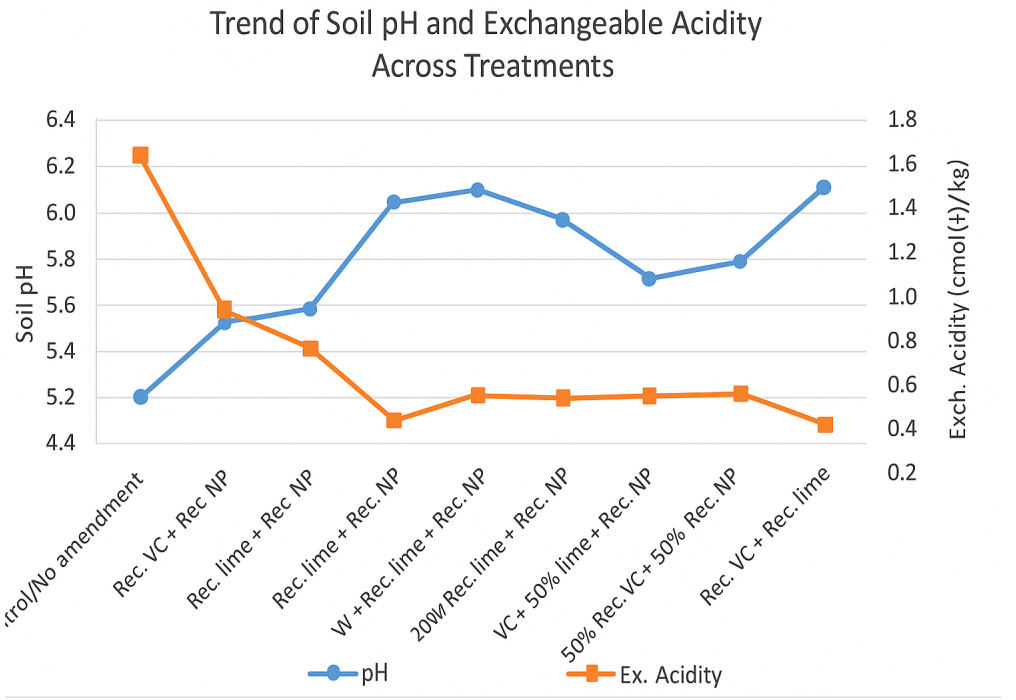

Figure 2. Trend of Integrated effect of lime and vermicompost on Soil pH and Exchangeable acidity

Statistical analysis of soil data showed that applying vermicompost with lime significantly increased soil nitrogen and available phosphorus content (Table 4). The observed improvements in soil fertility may be attributed to the enhancement of nutrient mineralization and availability due to lime and compost application. Liming acidic soils promotes phosphorus release and availability by improving root growth, alleviating Al toxicity, and allowing greater root elongation. The increase in soil nitrogen from lime and vermicompost application may be due to nutrient mineralization and the relationship between soil water pH and organic carbon (OC).

Fageria and Baligar (2008) reported that applying lime and vermicompost to acidic soils improves the soil environment for plant growth by increasing soil pH and nutrient availability. A more favorable root environment results from desirable soil pH levels, reduced Al and Mn toxicity, increased Ca and Mg availability, enhanced phosphorus and molybdenum uptake, and improved organic matter mineralization. These changes ultimately lead to better nitrogen, phosphorus, and sulfur uptake and enhanced soil biological activity. The results of this study showed no statistically significant differences in organic carbon levels among treatments. However, OC increased by 12.7% over the control in response to lime and vermicompost application.

4. Conclusion and Recommendations

Soil acidity is a major constraint to agricultural productivity in Ethiopia. Despite its negative impact on crop production, limited research has examined the combined use of organic and inorganic soil amendments to address this problem. This study evaluated the effects of integrated application of lime and vermicompost (VC) on soil chemical properties and barley productivity.

The results indicated that key agronomic parameters, including spike length, grain yield, dry biomass yield, and thousand-grain weight, were significantly improved by the combined application of lime and vermicompost. The highest grain yield was obtained from the treatment receiving 2.3 t ha^{-1} vermicompost combined with 1.3 t ha^{-1} lime, which resulted in a 156.3% increase compared to the untreated control. Moreover, the integrated use of lime and vermicompost significantly increased soil pH, reduced exchangeable acidity, and enhanced available phosphorus, thereby improving soil fertility and nutrient availability.

The study demonstrates that the combined application of lime and vermicompost is more effective than their sole application in mitigating soil acidity and improving barley yield. Therefore, the integrated use of organic and inorganic soil amendments is recommended as a sustainable strategy for improving soil health and crop productivity in acid-affected areas of Ethiopia.

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Evaluating Drip Irrigation and Plastic Mulching Effects on Tomato Yield and Water Use Efficiency in Fogera District, Lake Tana Basin, Ethiopia

Habtamu Abay Eshetie[1,2]

[1]Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box: 79, Bahir Dar, Ethiopia
[2]Department of Water Resource and Irrigation Engineering, Kombolcha Institute of Technology, Wollo University, Kombolcha, Ethiopia
Corresponding author: habtie229@gmail.com

Abstract

Water scarcity and inefficient irrigation are major constraints to tomato production in major growing regions. Field experiment was conducted over two growing seasons (2023–2024). This study evaluated the effects of irrigation method (furrow, drip without mulch, and drip with plastic mulch) and irrigation level (60%, 80%, and 100% of readily available water, RAW) on tomato yield, water use efficiency (WUE), and soil moisture dynamics at the Shina Farmer Training Center, Fogera District, Ethiopia. Results demonstrated that drip irrigation combined with plastic mulch significantly improved soil moisture stability, reduced evapotranspiration losses, and enhanced both yield and WUE relative to furrow irrigation and non-mulched treatments. The highest yield (8.41 t/ha) and WUE (11.46 kg/m³) were observed under 80% RAW with mulched drip irrigation, highlighting an effective water-saving strategy with minimal yield reduction. Two-way ANOVA revealed significant interactions between irrigation method and level on yield and WUE ($p < 0.05$), emphasizing the importance of optimized irrigation scheduling. These findings provide field-based evidence for climate-smart, resource-efficient agronomic practices suitable for semi-arid smallholder farming systems.

Keywords: Climate-smart agriculture, Irrigation Method, Irrigation Water Management, Soil moisture dynamics

1. Introduction

Water scarcity poses an increasing challenge for global agriculture, particularly in semi-arid and sub-humid areas where rainfall patterns are erratic and water resources are limited (Halder & Bose, 2024; Santos Pereira, 2005). In Ethiopia's Tana Sub-Basin, agriculture remains the backbone of rural livelihoods; however, unsustainable water management practices threaten food security and productivity (Teferi *et al*., 2025). Traditional irrigation methods, such as flood irrigation, dominate the region, but they are characterized by high water losses through evaporation, runoff, and deep percolation (Biswas *et al*., 2025). As climate variability intensifies and water demand rises, the adoption of efficient irrigation technologies that conserve water and enhance water use efficiency (WUE) is critical (Alharbi *et al*., 2024; Melkie *et al*., 2024).

Drip irrigation and plastic mulching are widely recognized as effective technologies to optimize water use and increase crop productivity (Bhargav & Subbaiah, 2024; Bwire *et al*., 2024; Mohanpuria *et al*., 2024; Santosh *et al*., 2024). Drip irrigation delivers water directly to the crop root zone, thereby minimizing evaporation, reducing non-beneficial water losses, and improving nutrient uptake efficiency (Mansingh *et al*., ; 2023Ma *et al*., 2022). Plastic

mulching further enhances irrigation efficiency by suppressing weed growth, regulating soil temperature, reducing surface evaporation, and conserving soil moisture (Demo & Asefa, 2024; Khose *et al*., 2023; Zhang *et al*., 2023; Kader *et al*., 2017).

The combined efficiency of drip irrigation and plastic mulch depends on soil type, climate, crop characteristics, and management practices (Huang *et al*., 2024; Wang *et al*., 2024; He *et al*., 2013;). Numerous studies worldwide have reported significant benefits of these technologies. For example, transitioning from furrow to drip irrigation has been shown to reduce water use by up to 60.4% for maize and 33.1% for onions, while simultaneously increasing yields (Mekonen Tiku *et al*., 2019; Karimi & Gomrokchi, 2011). Similarly, drip irrigation improved WUE in groundnut crops by 25% (Narayanamoorthy *et al*., 2020) and in tomatoes by enhancing both yields and water productivity compared to traditional methods (Yohannes & Tadesse, 1998; Pruitt *et al*., 1990).

Mulching complements drip irrigation by reducing soil evaporation and sustaining crop growth under limited water conditions (Shaikh *et al*., 2023; Mkhabela *et al*., 2019). Studies indicate that drip irrigation combined with mulch can save more than 50% of irrigation water, increase yields by 7–20%, and improve WUE by 12–69% compared to non-mulched systems (Li *et al*., 2024; Zhang *et al*., 2022; Biswas *et al*., 2015; Jemberu Lakew *et al*., 2014; Antonio *et al*., 2007; Ngouajio *et al*., 2007;).

Despite global evidence, there is limited research on the combined effects of drip irrigation and plastic mulching under local field conditions in the Tana Sub-Basin. Information is lacking in soil moisture dynamics and irrigation water productivity in tomato production, a high-value crop in the region. Therefore, the objective of this study was to evaluate the effects of drip irrigation and plastic mulching on tomato yield, water use efficiency (WUE), and soil moisture dynamics under field conditions at the Shina Experimental Site, Fogera District, in the Tana Sub-Basin, Ethiopia. The study aimed to (i) compare tomato yield performance under drip irrigation with and without plastic mulch across two growing seasons, and (ii) assess the influence of plastic mulch on soil moisture conservation and irrigation water productivity.

2. Material and Methods

2.1. Study area

The field experiment was conducted at the Shina Farmer Training Center (FTC), Fogera District, in the Tana Sub-Basin, northwestern Ethiopia (Figure 1). The site is situated at an elevation of 1800 meters above sea level, with coordinates 11.88°N and 37.64°E. The area has a sub-humid climate, with a mean annual rainfall of approximately 1,342 mm, and average maximum and minimum temperatures of 29.5°C and 24°C, respectively. Soils at the experimental site was classified as vertisols or clay loam, with a bulk density of 1.36 g cm^{-3}, field capacity of 24.9%, and permanent wilting point of 16.8%, determined during this study.

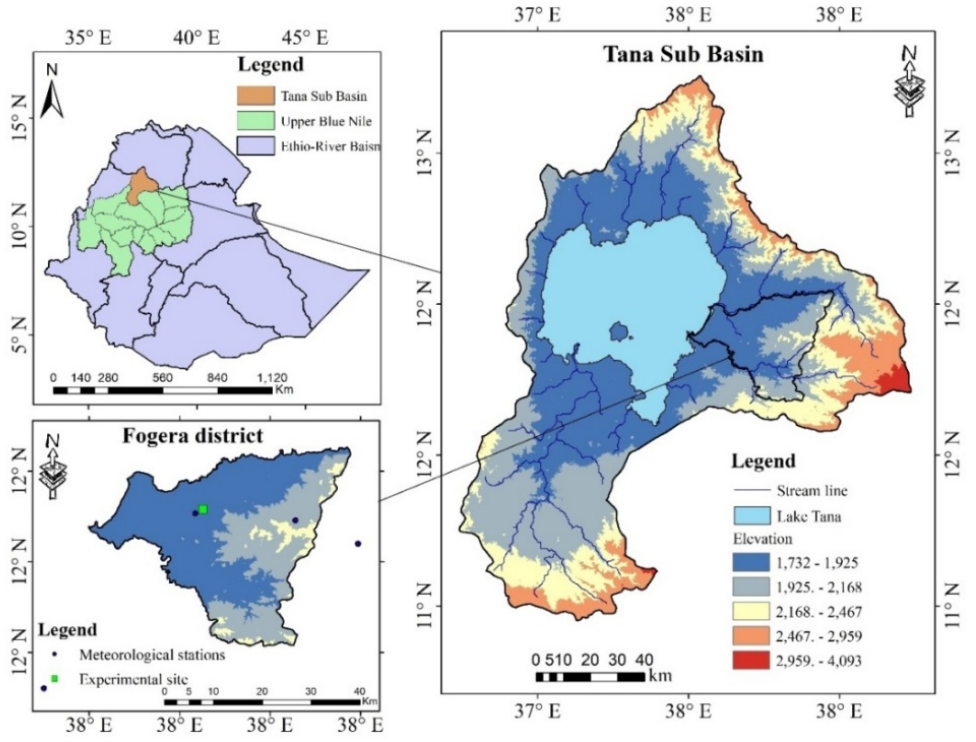

Figure 1. The location of the study area (experimental site) at Farmer Training Center (FTC), Shina Kebele, Fogera district, Ethiopia.

2.2. Experimental design and treatments

The study evaluated three irrigation methods: furrow irrigation (control), drip irrigation without mulch, and drip irrigation with plastic mulch. Each method was combined with three irrigation levels corresponding to 60%, 80%, and 100% of the readily available water (RAW) in the crop root zone. Plant spacing was 40 cm within rows and 80 cm between rows.

A randomized complete block design (RCBD) was applied, with treatments randomly assigned within blocks. This factorial arrangement produced nine treatments: T1: Drip + mulch at 100% RAW, T2: Drip + mulch at 80% RAW, T3: Drip + mulch at 60% RAW, T4: Drip without mulch at 100% RAW, T5: Drip without mulch at 80% RAW, T6: Drip without mulch at 60% RAW, T7: Furrow irrigation at 100% RAW (control), T8: Furrow irrigation at 80% RAW, and T9: Furrow irrigation at 60% RAW. The detailed layout of the experimental plots, including plot size, row spacing, and plant spacing, is shown in Figure 2. The experiment was conducted over two consecutive growing seasons (2023 and 2024) to account for seasonal variability.

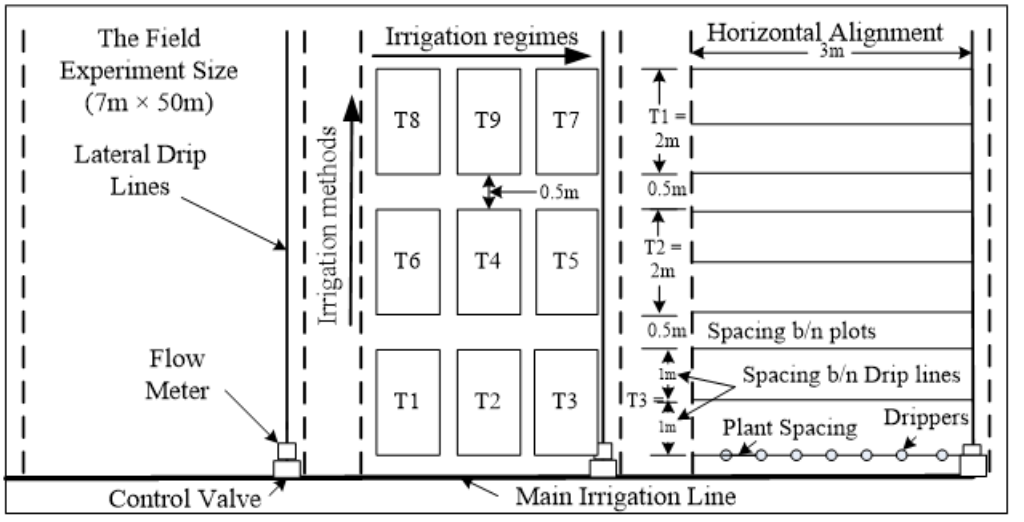

Figure 2. The layout of the field experimental design with three irrigation treatments.

2.3. Planting and fertilizer management: A locally adapted tomato variety suitable for the Fogera experimental site was used. Planting occurred on January 1, 2023, and January 3, 2024, with harvesting completed by May 30 in both seasons. Nitrogen (N) fertilizer was applied at 180–220 kg ha^{-1} in three split doses: 70 kg ha^{-1} at transplanting, 65 kg ha^{-1} at the 4–6 leaf stage, and 65 kg ha^{-1} at early fruit set. Phosphorus (P_2O_5) was applied at 90 kg ha^{-1} during transplanting (Yusuf *et al*., 2023; Yan *et al*., 2022; Filho *et al*., 2020;).

2.4. Irrigation setup and materials

Two irrigation systems were employed: drip and furrow irrigation, both supplied by a 1,000-liter water storage tank powered by a solar-driven pump. The drip system consisted of HDPE pipes with in-line emitters for uniform water distribution. Some plots (T1–T3) were covered with black plastic mulch (0.025 mm thick), while others (T4–T9) remained bare. Furrow irrigation was applied through traditional channels; with water volumes measured using a Parshall flume for furrow plots and a calibrated water meter for drip plots. All materials were provided by the Amhara Bureau of Agriculture and allocated to Shina FTC.

2.5. Weather data and estimation of crop evapotranspiration

Daily weather data, including maximum and minimum temperature, relative humidity, solar radiation, wind speed, and rainfall, were obtained from the Ethiopian National Meteorological Agency, Bahir Dar branch, for five meteorological stations located near the experimental site (Figure 1). Reference evapotranspiration (ETo) was estimated using the FAO-56 Penman–Monteith equation (Allen *et al*., 1998):

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T}+273}\mathrm{U_2}(\mathrm{e_a} - \mathrm{e_d})}{\Delta + \gamma(1 + 0.34\mathrm{U_2})} \quad (1)$$

Where ET_0 is the reference evapotranspiration (mm day^{-1}) Rn is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is daily mean air temperature at a height of 2 m (◦C), U_2 is the wind speed at a height of 2 m (m s^{-1}), ed is

saturation vapor pressure at the air temperature (kPa), e_a is actual vapor pressure, (kPa) is the slope of the saturation water vapor pressure-temperature curve, and (kPa $\circ C^{-1}$) is the psychometric constant (kPa $\circ C^{-1}$).

Crop evapotranspiration (ETc, mm/day) for tomato was estimated as:

$$ET_c = ET_O \times K_C \quad (2)$$

Where Kc is the crop coefficient at different growth stages.

2.6. Irrigation scheduling and soil moisture monitoring

Irrigation was scheduled based on measured soil moisture depletion. Total available water (TAW) in the tomato root zone was computed as the difference between field capacity and permanent wilting point. Soil moisture was monitored weekly at three depths (0–30, 30–60, 60–90 cm) to determine irrigation timing and depth. Three irrigation levels were applied by replenishing 100%, 80%, or 60% of the depleted TAW, with irrigation triggered when 50% of TAW was depleted, following FAO guidelines for tomato irrigation (Allen *et al*., 1998). Irrigation depth (I, mm) was calculated using:

$$I = AD \times AWC \times Z \times p_b \quad (3)$$

Where I = irritation depth, AD is allowable depletion factor in % (50% for tomato), AWC is available water content per unit depth (mm/cm), Z is effective root zone depth (cm) and p_b is soil bulk density (g/cm^3). Irrigation interval (days) was determined as:

$$Interval = \frac{I}{ET_C} \quad (4)$$

2.7. Data collection

2.7.1. Agronomic and flow measurements

Tomato yield (kg/ha) was recorded from each plot in both seasons. Irrigation volumes were recorded throughout the experiment, allowing accurate calculation of water use efficiency (Amare *et al*., 2024; Ahmee & Berhanu, 2020).

2.7.2. Water use efficiency estimation

Water Use Efficiency (WUE) represents a crop's ability to produce yield per unit of water consumed during the growing season (Alharbi *et al*., 2024). This metric is a key indicator of how effectively a crop utilizes available water for growth and productivity (Zwart & Bastiaanssen, 2004; Igbadun *et al*., 2006) and critical for optimizing irrigation practices (Soujanya & Gurjar, 2024). WUE was calculated using the following formula:

$$WUE = \frac{Crop\ Yield\ (kg/ha)}{Total\ water\ used\ (mm\ of\ water\ applied)} \quad (5)$$

2.7.3 Soil moisture measurements

Undisturbed soil samples were collected for laboratory analysis to determine field capacity, permanent wilting point, and bulk density. Weekly soil moisture measurements supported irrigation scheduling and assessment of water dynamics throughout the growing seasons.

2.8. Data analysis

Treatment effects on yield and WUE were analyzed using two-way factorial ANOVA in RStudio, with irrigation method and level as factors. Significant differences among treatments were determined using Tukey's HSD post-hoc test at a 95% confidence level ($p < 0.05$). Weekly soil moisture was summarized as mean ± standard deviation. Correlations between WUE, yield, and total water applied were calculated using Pearson's coefficient.

3. Results and Discussion

3.1. Results

3.1.1 Seasonal crop evapotranspiration

Crop evapotranspiration (ETc) exhibited clear temporal variation across the two growing seasons, closely following the crop growth stages (Figure 3). In 2023, ETc values during the initial stage in early January ranged from 1.6 to 2.4 mm/day, reflecting minimal water demand of young plants. ETc progressively increased during the developmental and mid/reproductive stages, peaking on 27 January, 16 February, and 17 March at 5.9 mm/day. During the late/maturity stage, ETc gradually declined, indicating reduced water demand as the crop approached physiological maturity.

In 2024, initial-stage ETc values were slightly lower (1.4–2.3 mm/day), but developmental and mid/reproductive stages exhibited sharper increases, with peak ETc values between 3.7 and 4.4 mm/day. The late/maturity stage showed a similar declining trend as in 2023. These results highlight the dynamic water requirements of tomato at different growth stages, indicating optimized irrigation scheduling.

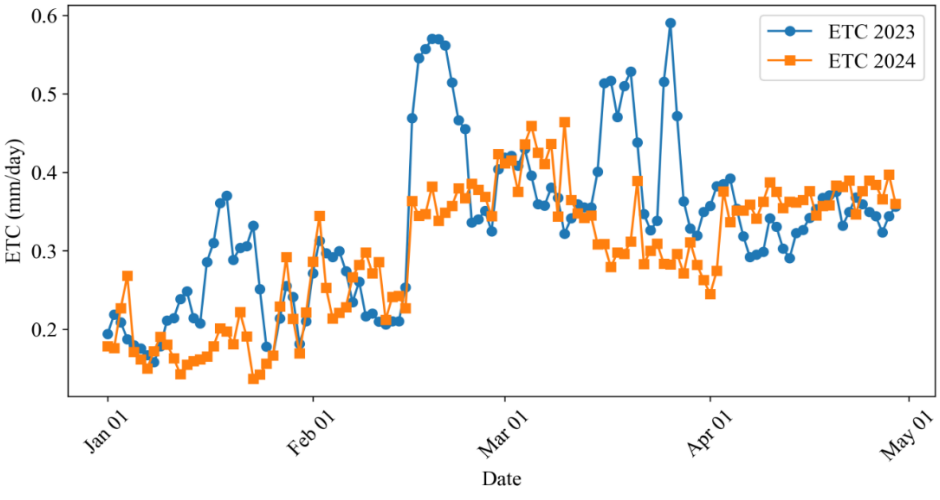

Figure 3. Daily crop evapotranspiration (ETc, mm/day) in 2023 and 2024 seasons, showing variations across crop growth stages: initial, developmental, mid/reproductive, and late/maturity.

3.1.2. Irrigation water applied

Irrigation water applied varied significantly among treatments and seasons (Table 1). Furrow irrigation treatments (T7–T9) received the highest volumes, with T7 (100% RAW) applying 1,207.46 mm in 2023 and 1,056.13 mm in 2024. Drip irrigation with plastic mulch (T1–T3) applied similar amounts of water as drip without mulch (T4–T6). For instance, T1 (drip + mulch at 100% RAW) and T4 (drip without mulch at 100% RAW) applied 1,007.46 mm in 2023 and 856.13 mm in 2024. Treatments at lower irrigation levels (60% RAW; T3, T6, T9) applied the least water, with mean values ranging from 639.08 mm to 839.08 mm. Standard deviations across individual treatments were moderate (45.40–75.66 mm), reflecting consistent irrigation management between seasons, while the overall standard deviation across all treatments and seasons was 152.22 mm, indicating that treatment differences, rather than seasonal variation, primarily drove water application variability.

Table 1. Total irrigation water applied (mm) per treatment and season with standard deviation.

Treatment	2023	2024	Mean	STDV
T1	1007.46	856.132	931.797	75.6649
T2	845.969	724.905	785.437	60.5319
T3	684.477	593.679	639.078	45.3989
T4	1007.46	856.132	931.797	75.6649
T5	845.969	724.905	785.437	60.5319
T6	684.477	593.679	639.078	45.3989
T7	1207.46	1056.13	1131.8	75.6649
T8	1045.97	924.905	985.437	60.5319
T9	884.477	793.679	839.078	45.3989
STDV	162.097	142.72	152.216	

3.1.3. Soil moisture dynamics

Weekly soil moisture dynamics showed clear differences among treatments across the two growing seasons (Figure 4). In 2023, the highest mean soil moisture content was maintained under T1 (drip + mulch, 100% RAW), ranging from 0.249 to 0.125 cm^3/cm^3, followed closely by T2 (drip without mulch, 100% RAW) with 0.248 to 0.124 cm^3/cm^3. T4 (drip + mulch, 80% RAW) and T5 (drip without mulch, 80% RAW) also retained relatively high soil moisture, with values of 0.239–0.119 cm^3/cm^3 and 0.238–0.118 cm^3/cm^3, respectively. Intermediate treatments such as T3 (drip + mulch, 60% RAW) and T6 (drip without mulch, 60% RAW) showed lower values, ranging from 0.203–0.102 cm^3/cm^3 and 0.202–0.100 cm^3/cm^3, respectively. Furrow irrigation treatments consistently recorded lower soil moisture compared to drip irrigation: T7 (furrow, 100% RAW) ranged from 0.209 to 0.084 cm^3/cm^3, T8 (furrow, 80% RAW) from 0.198 to 0.078 cm^3/cm^3, and T9 (furrow, 60% RAW) showed the lowest values, dropping from 0.162 to 0.060 cm^3/cm^3. Similar trends were observed in 2024, with only slight differences compared to the 2023 season. T1 and T2 again maintained the highest soil moisture, ranging from 0.249 to 0.124 cm^3/cm^3 and 0.247 to 0.123 cm^3/cm^3, respectively, followed by T4 and T5 with 0.239–0.120 cm^3/cm^3 and 0.238–0.118 cm^3/cm^3. Deficit irrigation treatments (T6 and T9) again recorded the lowest values, with T9 showing the most severe depletion (0.162–0.060 cm^3/cm^3).

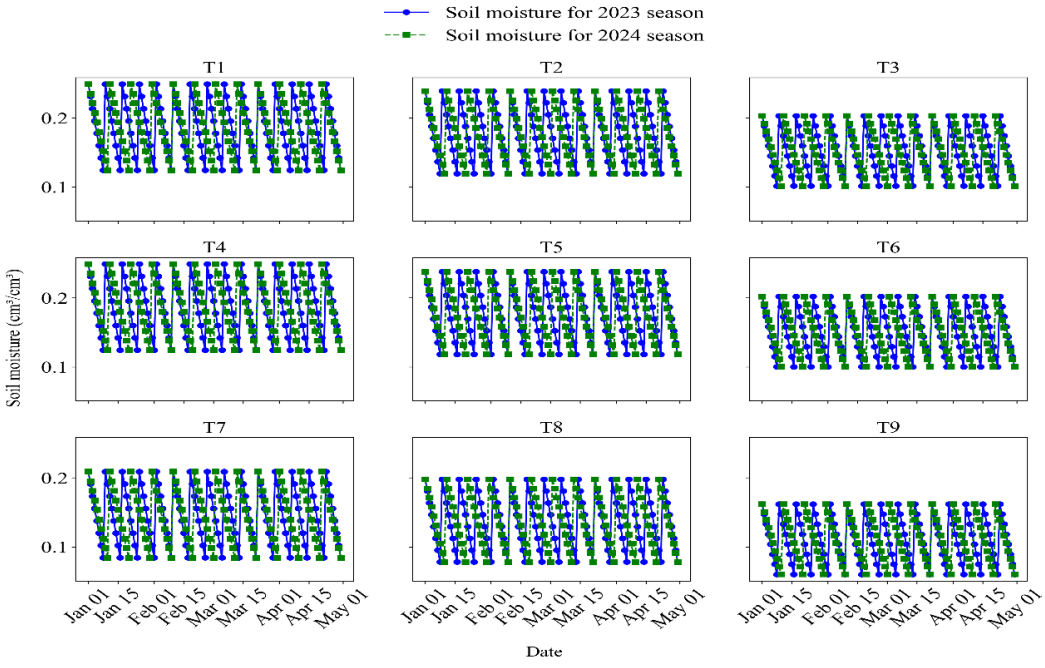

Figure 4. Soil moisture dynamics (volumetric water content, %) at 0–90 cm depths for treatments T1–T9 in 2023 and 2024.

The soil moisture content varied across treatments, depths, and seasons, with an overall mean of 16.12% and a standard deviation of 2.43%. Variation across soil depths was relatively uniform, with standard deviations of 2.43% (0–30 cm), 2.40% (30–60 cm), and 2.43% (60–90 cm), indicating consistent moisture distribution within the root zone. Seasonal variability was also limited, with standard deviations of 2.44% in 2023 and 2.41% in 2024, suggesting that inter-annual climatic differences had only a minor effect on soil water availability. Differences across treatments were more pronounced, with a treatment-level standard deviation of 2.51%. Among treatments, the highest mean soil moisture was recorded in T1 (18.67%) and T2 (18.66%) under drip irrigation at 100% and 80% RAW, whereas the lowest value was found in T9 (11.65%) under furrow irrigation at 60% RAW.

Table 2. Mean soil moisture (%) at different depths per treatment and season.

Treatments	2023 Season			2024 Season		
	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm
T1	18.67	20.20	21.73	18.68	18.68	20.21
T2	18.66	18.67	18.69	18.66	18.66	18.66
T3	15.23	15.25	15.27	15.24	15.24	15.24
T4	17.92	17.94	17.95	17.93	17.93	17.93
T5	17.80	17.82	17.83	17.81	17.81	17.81
T6	15.01	15.03	15.05	15.02	15.02	15.02
T7	14.66	14.67	14.69	14.66	14.66	14.66
T8	13.80	13.82	13.83	13.81	13.81	13.81
T9	11.11	12.65	14.18	11.12	11.12	12.65

3.1.4 Tomato yield and water use efficiency

Tomato yield and water use efficiency (WUE) showed significant variation among irrigation treatments and between the two growing seasons (Table 3). In 2023, yields ranged from 1.31 t/ha (T9) to 8.21 t/ha (T1), while in 2024, yields ranged from 1.51 t/ha (T9) to 8.41 t/ha (T1). The highest yields were consistently obtained under drip irrigation with plastic mulch (T1 and T2), whereas the lowest yields were observed under furrow irrigation (T7–T9). Similarly, WUE values ranged from 1.32–9.58 kg/m³ in 2023 and 1.69–11.46 kg/m³ in 2024, with mulched drip irrigation treatments (T1, T2) showing substantially higher efficiency compared to non-mulched and furrow systems.

Table 3. Tomato yield (t/ha) and water use efficiency (kg/m³) under different irrigation treatments across two seasons (2023 and 2024).

Treatment	Yield 2023 (t/ha)	Yield 2024 (t/ha)	Mean Yield (t/ha)	WUE 2023 (kg/ha/mm)	WUE 2024 (kg/ha/mm)
T1	8.21	8.41	8.31	8.15	9.82
T2	8.11	8.30	8.21	9.58	11.46
T3	4.20	4.40	4.30	6.14	7.41
T4	5.38	5.58	5.48	5.34	6.52
T5	5.44	5.64	5.54	6.43	7.77
T6	4.07	4.27	4.17	5.94	7.19
T7	1.59	1.61	1.60	1.32	1.52
T8	1.45	1.55	1.50	1.39	1.67
T9	1.31	1.51	1.41	1.48	1.90

The two-way ANOVA indicated that irrigation system, irrigation level, and their interaction significantly affected both yield and WUE ($p < 0.05$; Table 5). Post-hoc comparisons using Tukey HSD revealed that T1 and T2 were in the highest significance group (A) for yield, while furrow treatments (T7–T9) were in the lowest significance groups (D–E) (Table 6). WUE showed a similar pattern, with mulched treatments significantly outperforming non-mulched treatments.

Table 5. Two-way ANOVA summary for tomato yield and WUE.

Source of Variation	Yield				WUE			
	Sun of Squares	Df	F-value	p-value	Sun of Squares	Df	F-value	p-value
Irrigation system	3.2×10^7	2	312, 841	0.0051	12.7	2	102.38	0.00585
Irrigation level	2.23×10^7	2	211, 930	0.0178	9.4	2	87.52	0.01455
Irrigation system × Level	1.34×10^7	4	63, 977	0.0054	6.2	4	45.81	0.00587
Residual	945	18	-		-	18	-	

Note: df = degrees of freedom, F-value = ANOVA statistic (variance between groups / variance within groups) and p-value = probability differences occurred by chance; $p < 0.05$ indicates significance.

Table 6. Tukey HSD pairwise comparisons of treatment yield and WUE (α = 0.05).

Treatment	Tukey Groups Yield	Tukey Group WUE
T2	A	A
T1	A	B
T5	B	C
T3	B	C
T6	C	C
T4	C	D
T9	C	D
T8	C	E
T7	D	E

Note*:* Treatments sharing the same letter are not significantly different at $p < 0.05$.

Compared with the control treatment (T7) drip irrigation with mulch resulted substantial improvements. In 2023, T1 and T2 increased yields by 416% and 410%, respectively, while in 2024 the increases were 423% each. WUE improvements were even higher, with T2 achieving 628% in 2023 and 653% in 2024, followed by T1 with 519% & 545%, respectively. By contrast, the lowest-performing treatments (T8 and T9) showed negative yield responses relative to the control, despite slight WUE improvements.

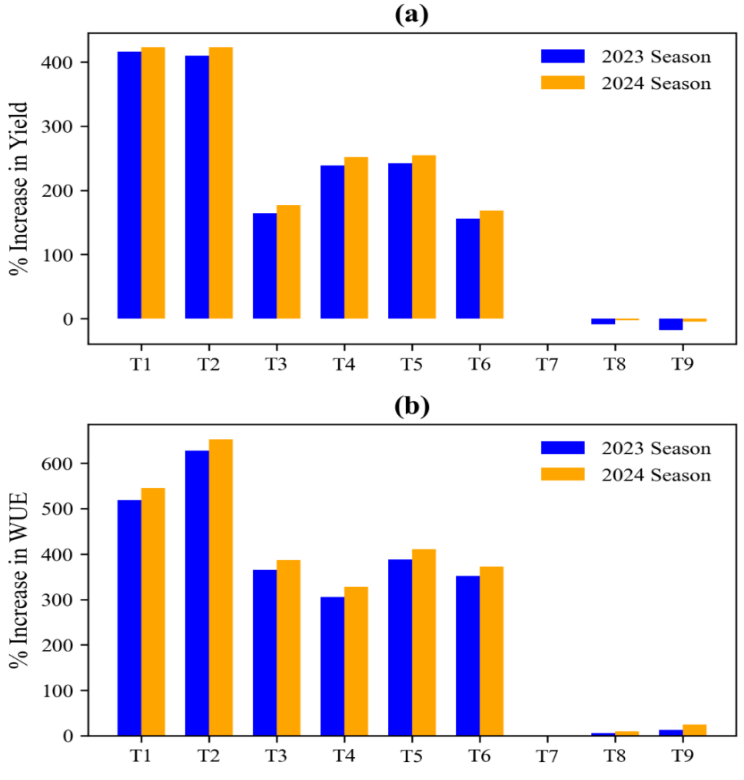

Figure 5. Percentage increase in tomato yield (5a) and water use efficiency (5b) relative to the control treatment (T7) under different irrigation treatments for the 2023 and 2024 growing seasons.

The result in Figure 5 illustrates that mulched treatments outperformed non-mulched treatments in both years, with yield and WUE advantages being more pronounced in 2024. Compared with non-mulched treatments, the application of plastic mulch increased tomato yield by approximately 5–15% and WUE by 15–25% on average, depending on the irrigation level. This improvement highlights the effectiveness of mulch in reducing soil evaporation, conserving water and enhancing crop productivity per unit of water applied.

3.2. Discussion

3.2.1. Soil moisture retention and irrigation efficiency

Mulched drip treatments consistently maintained the highest soil moisture, stabilizing root-zone water and enhancing irrigation efficiency. Mulched drip treatments (T1–T3) consistently maintained the highest soil moisture (15.23%–18.67%), demonstrating that plastic mulch effectively reduces evaporation and stabilizes root-zone water. By acting as a physical barrier, mulch conserves water during periods of high evaporative demand, providing a more uniform moisture environment that supports root development, nutrient uptake, and physiological activity (Mishra & Mishra, 2023; Debele *et al*., 2022).

Drip irrigation without mulch (T4–T6) still delivered substantial moisture to the root zone (15.01%–17.92%), yet minor fluctuations occurred due to surface evaporation, highlighting the additive benefit of mulch in maintaining consistent moisture. Furrow irrigation (T7–T9), particularly under deficit irrigation (T9, 11.64%), exhibited rapid moisture declines post-irrigation, reflecting the lower efficiency of surface methods in maintaining stable root-zone water (Aiyelari *et al*., 2022; Patel *et al*., 2021). This pattern suggested that irrigation method primarily governs water distribution efficiency, while mulch is essential for mitigating short-term moisture variability and improving water availability during critical crop growth stages.

Total irrigation volumes were strongly influenced by both irrigation method and applied level. Furrow irrigation required the highest amounts due to losses from runoff, deep percolation, and evaporation. Drip treatments, with or without mulch, applied similar volumes, indicating that mulch modestly reduces surface evaporation but does not substantially alter total irrigation requirements when scheduling is precise (Demo & Asefa, 2024). Treatments at 60% RAW consumed the least water, emphasizing that applied irrigation level is the main driver of water savings, while mulch provides an additional buffer to stabilize root-zone moisture and reduce temporal fluctuations (Baki *et al*., 2024; Biswas *et al*., 2015; Panigrahi *et al*., 2010;). Efficient water delivery through mulched drip irrigation supports higher water use efficiency (WUE) by minimizing losses and maintaining consistent access to soil moisture, which directly benefits crop growth and productivity.

3.2.2. Effects of irrigation and mulch on tomato productivity and water efficiency

Mulched drip treatments (T1 and T2) consistently produced the highest tomato yields and water use efficiency (WUE) across both 2023 and 2024 seasons, with increases of up to 423% in yield and 653% in WUE relative to the control. These superior performances can be directly attributed to the stable and elevated root-zone soil moisture maintained under mulched drip irrigation (Figure 4). Mulch acts as a physical barrier, reducing surface evaporation and maintaining uniform soil moisture throughout the 0–90 cm root zone, which supports continuous water availability during critical growth stages such as flowering

and fruit set. The consistent soil moisture profile enhances photosynthetic activity, nutrient uptake, and biomass accumulation, translating into higher yields and improved water productivity (Kishore *et al*., 2022; Berihun, 2023; Li *et al*., 2024). The high WUE observed in T1 and T2 indicates that a larger proportion of applied water was effectively utilized by the crop rather than lost through evaporation or deep percolation, highlighting the efficiency of mulched drip systems.

Non-mulched drip treatments (T4–T6) achieved moderately high yields and WUE, but these were consistently lower than mulched plots. Root-zone soil moisture in these plots (15.01%–17.92%) was still sufficient to support crop growth, but minor fluctuations occurred due to surface evaporation, particularly during periods of high evaporative demand (Bo & Yao, 2025; Kumar *et al*., 2021; Kiptoo *et al*., 2018). These fluctuations led to short-term water stress within the root zone, slightly limiting photosynthesis and nutrient uptake and explaining the lower yield and WUE relative to mulched plots. Among non-mulched plots, T4 at 100% RAW maintained the highest root-zone moisture, resulting in the best performance within this group, whereas T6 at 60% RAW experienced larger moisture deficits, further reducing yield and water productivity. Furrow irrigation treatments (T7–T9) displayed the lowest yields and WUE, despite full irrigation in T7 and T8. Rapid post-irrigation moisture declines and uneven water distribution across the root zone (especially in T9, 60% RAW) reduced water availability for crop uptake. Losses through surface evaporation, runoff, and deep percolation limited the effective water used by the crop, directly lowering yield and WUE (Aiyelari *et al*., 2022; Patel *et al*., 2021).

Deficit irrigation at 60% RAW further illustrates the sensitivity of tomato to soil moisture stress. Mulched plots under deficit irrigation (T3) maintained higher root-zone moisture than non-mulched plots (T6), mitigating some of the negative effects on growth and yield. However, reductions in both yield and WUE under these deficit conditions demonstrated that mulch alone cannot fully compensate for insufficient water supply. These results confirmed that root-zone soil moisture dynamics are the primary driver of variations in tomato yield and WUE, with mulching enhancing retention and drip irrigation ensuring targeted delivery, while surface irrigation fails to provide stable water access. These findings showed that integrating plastic mulch with drip irrigation stabilizes root-zone moisture, buffers crops against short-term water deficits, and maximizes the efficiency of applied water, leading to superior tomato yield and WUE compared with non-mulched or furrow-irrigated systems.

3.3.3 Practical implications for semi-arid production

The integration of plastic mulch with drip irrigation maximizes yield and WUE while stabilizing the root-zone environment, buffering crops against water stress and seasonal variability. Mulched drip irrigation represents a highly efficient and sustainable practice for smallholder tomato production in semi-arid regions. By reducing water losses, enhancing soil moisture retention, and improving water productivity, these practices can contribute to more reliable crop performance under variable climatic conditions. Additionally, proper irrigation scheduling remains critical, particularly under deficit conditions, to ensure that soil moisture remains sufficient during critical growth stages. Collectively, the results highlight the synergistic effects of irrigation method, applied water level, and mulch in optimizing soil

moisture dynamics, crop growth, and water use efficiency, offering a practical and resource-efficient strategy for enhancing tomato productivity in water-limited agro ecosystems.

4. Conclusion and Recommendations

Drip irrigation combined with plastic mulch markedly improved tomato yield and water use efficiency under semi-arid conditions in Fogera District. Mulched treatments stabilized root-zone soil moisture, reduced surface evaporation, and conserved irrigation water, with 80% RAW achieving comparable yields to 100% RAW while lowering depth of water applied, offering a practical water-saving strategy without significant yield loss. Non-mulched drip irrigation increased yields over furrow irrigation but remained less efficient due to greater soil moisture fluctuations and higher evaporation losses, while furrow irrigation exhibited the lowest water use efficiency. These findings indicate that adopting mulched drip irrigation, particularly at 80% RAW, offers smallholder farmers a sustainable and resource-efficient approach to enhance productivity. Extension support and farmer training are recommended to facilitate adoption, and further research should assess long-term economic viability and performance across diverse agro-ecological zones.

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Evaluation of Bio.SoilZ and Bio. PlantZ Stimulants in Improving Teff Productivity at Tahtay Koraro District, Northern Ethiopia

Solomon Mebrahtom*, Tewolde Berhe, Tsadik Tadele, Kinfe Tekulu, Goitom Aregawi, Weldegebriel Gebrehiwot, Gebresemaeti Kahsu, and Samrawit Mebrahtu

Department of Soil Fertility Research, Shire Soil Research Centre, Tigray Agricultural Research Institute, P.O. Box 40, Shire, Ethiopia
* Corresponding author: solomon.mebrahtom08@gmail.com

Abstract

The Bio.SoilZ technology aims to promote environmentally sustainable farming practices; however, limited research has been conducted on its effects. This study assessed the impact of Bio.SoilZ and Bio.PlantZ stimulants on teff yield and yield components. A field experiment was conducted during the 2024 cropping season using a randomized complete block design across three farmers' fields with nine treatments. The treatments included combinations of recommended NP fertilizer (RNP) rates (25%, 50%, 75%, and 100%) with varying doses of Bio.SoilZ applied at sowing and Bio.PlantZ applied at the vegetative stage. The results showed that the application of Bio.SoilZ and Bio.PlantZ in combination with RNP had significant ($P < 0.05$) effects on plant height, straw yield, biomass yield, and grain yield. The treatment comprising 100% RNP + 20 L Bio.SoilZ at sowing + 20 L Bio.PlantZ at the vegetative stage produced the highest plant height (94.58 cm), straw yield (4955.6 kg ha^{-1}), biomass yield (7000 kg ha^{-1}), and grain yield (2044.4 kg ha^{-1}). In contrast, the unfertilized plot recorded the lowest values. This treatment increased teff grain yield by 12% compared with the recommended NP fertilizer alone. Partial budget analysis indicated that the same treatment was economically beneficial for farmers in the study area. Therefore, further on-farm studies across different soil types and crops are recommended to validate these findings.

Keyword: Bio-stimulant application, Economic analysis, On-farm experimentation, Sustainable agriculture, Yield enhancement

1. Introduction

Since ancient times, teff (Eragrostis tef (Zucc.) Trotter) has been a staple crop in Ethiopia, accounting for 30% of the country's land area and 20% of its overall cereal production (Abewa *et al.* 2019; Admassu, 2017). It contributes significantly to the provision of minerals, carbohydrates, and protein to society. It is a crop that is extensively grown between 1700 and 2400 meters above sea level and is adaptable to various agro-ecologies (Refissa, 2012; Amante, 2022). Maintaining soil fertility is crucial because only a small portion of the world's land area is suitable for agriculture worldwide (Merrill *et al.*, 2013). Regrettably, the use of chemical fertilizers in intensive farming methods has increased crop production. However, in impacted areas, the overuse and/or continuous use of chemical fertilizers has led to increasingly negative effects on soil quality and pollution of the environment (Savci 2012; Cao *et al.*, 2016; Ayilara *et al.*, 2020). Chemical fertilizers are used to alleviate these issues and increase productivity, according to a number of studies. However, when these fertilizers are applied improperly, they can cause soil degradation, including salinization, acidification, nutrient imbalance, and irregular nutrient accumulation in agricultural areas (Niu *et al.*, 2021). The two main categories of fertilization procedures are applying fertilizers to the soil

or roots of crops and applying fertilizers to the leaves of crops (Niu *et al.*, 2021). Compared to root fertilization, leaf fertilization allows for direct absorption through the leaves, enabling faster and more effective transport to other plant organs (Sathyanarayana, *et al.*, 2017). Furthermore, foliar fertilizer can be applied at the best times and concentrations to meet the unique needs of individual plants at different stages of growth. Compared to root fertilization, this kind of fertilization is better suited to the specific requirements of the plants (Aghighi *et al.*, 2020).

Foliar fertilizers are more important due to the scarcity of soil nutrients (Verma *et al.*, 2000). To improve nutrient absorption, promote development, and strengthen plant resistance to environmental challenges, bio-energetic compounds, also known as bio-stimulants, are used (Du Jardin, 2015; Ghatas, 2021). The Utilization of Bio.SoilZ and Bio.PlantZ has the potential to increase the nutrient content of the soil, PlantZ can enhance its micro-ecological habitat and functionality. Innovative Bio.SoilZ technology is intended to support environmentally friendly farming practices by improving soil organic matter, which results in more efficient water holding, increased carbon uptake from the atmosphere, and greater carbon storage in the soil, according to information from the company's website (https://biosoilz.com/). By adopting Bio.SoilZ technology, farmers benefit from improved soil fertility, reduced erosion, and increased resistance to harsh weather events like floods and droughts. However, there was insufficient information or publications to support the use of these products and how crops and/or soil responded to their application. Consequently, the objective of this research was to assess the impact of Bio.SoilZ fertilizer applied to the soil and the effects of Bio.PlantZ foliar fertilizer, both alone and in combination with mineral fertilizer, on Teff yield and yield attributes in the northern Ethiopian district of Tehtay Koraro.

2. Materials and Methods

2.1. Description of the experimental sites

The study was carried out on three farmers' farms in the Tahtay Koraro area in the northwest region of Tigray Regional State, northern Ethiopia, under rainfed conditions during the main cropping season of 2024. Mekelle, the regional capital, is about 310 kilometers away from Tahtay Koraro. Asigede Tsimbla, Laelay Adyabo, and Medebay-Zana border the district to the southwest, north, and southeast, respectively. Table 1 and Figure 1 provide a description of the experimental sites. According to Abbadi *et al.* (2024), most of the district area (81%) falls under the midland (Weyna-degua) agro-ecological zone (AEZ) categories.

Table 6: Description of the study sites in Tahtay Koraro district in northwestern zone

Sites	Site Codes	Kebele	Geocoordinates		
			N	E	Elevation (m.a.s.l)
1.	BioSPZ/001	Beles	14°03’46’’	38°24’02’’	1961
2.	BioSPZ/002	Beles	14°03’33’’	38°23’52’’	1937
3.	BioSPZ/003	Beles	14°04’30	38°23’24’’	1995

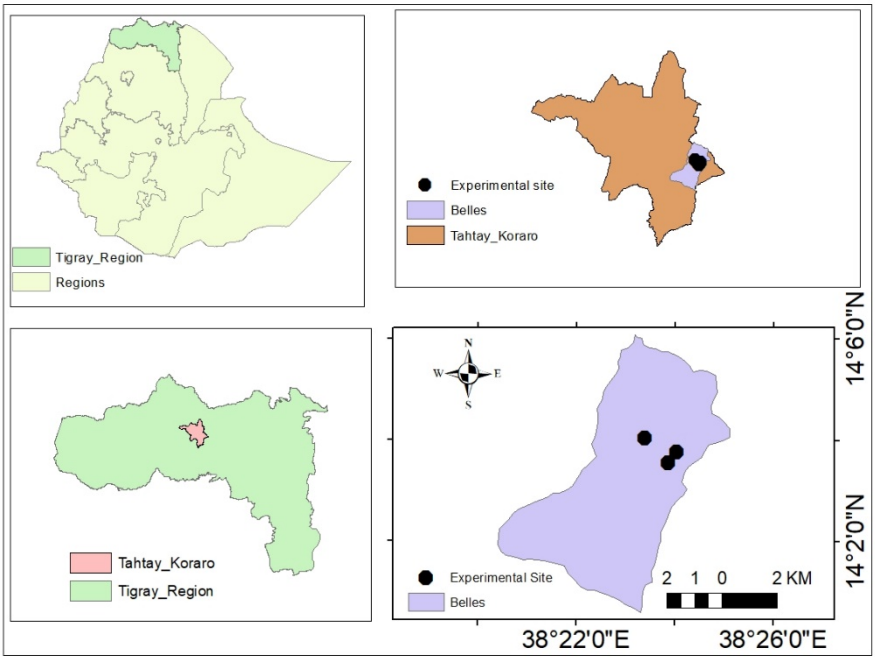

Figure 8. Map of the experimental sites

2.2. Site Selection, Soil Sampling and Analysis

From the district (T/Koraro), the teff producing potential kebele (Belles) was selected. As a result, three farmers' fields were selected for the 2024 cropping year based on their readiness to manage experimental fields. Before planting and after harvest, representative surface (0–20 cm) composite soil samples were collected from each experimental unit using the usual soil sampling protocol. After being air dried, the soil samples were run through a 2 mm sieve. Standard principles and procedures were modified to determine the qualities of the soil.

2.3. Experimental Design and Treatments

A total of nine treatments were used in the trial field study, which was replicated at three farmer fields using a randomized complete block design (RCBD) with three replications. In July 2024, the Teff variety "quncho" was planted on a 9 m2 plot (3 m by 3 m) at the suggested seed rate of 15 kg ha-1. The experiment employed NPS (19 kg ha-1 N, 38 kg ha-1 P2O5, and 7 kg ha-1 S) and urea (46 kg ha-1 N) as inorganic fertilizers. Therefore, the recommended NP for the study was 46 kg ha-1 N and 121 kg ha-1 NPS. For the production of tef, all other agronomic and management practices were used in accordance with study recommendations. In the experiment, nine treatments (Table 2) were assessed, including Bio.SoilZ and Bio.PlantZ. Both Bio.SoilZ and Bio.PlantZ liquid fertilizers were used separately and in combination with the recommended rates of N and P (RNP) from inorganic fertilizer sources of NPS (121 kg ha-1 NPS). As positive and negative controls, respectively, 100% RNP application and no input application were also included.

Table 7: Description of the Treatments

Treatments	**Description**
1.	Control
2.	100% RNP
3.	100% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage
4.	100% RNP + 10L BSZ at sowing + 10L BPZ at vegetative stage
5.	100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage
	75% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage
6.	50% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage
7.	25% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage
8.	5L BS at sowing + 5L BPZ at vegetative stage

RNP= the recommended rate of N and P**; BSZ=** Bio.SoilZ**; BPZ=** Bio.PlantZ

Note: Boi.PlantZ were applied at the same rate as the Bio.SoilZ at vegetative stage
Plot size = 3*3m; Plot and boarders spacing = 0.5m
Crop Variety = Quncho at 15 kg/ha seed rate.

50% of the total recommended N and all NPS dosages were applied as a basal application during planting, with the remaining 50% of N being top-dressed during the crop's tillering stage. According to the company's guidelines, both Bio.SoilZ and Bio.PlantZ stimulants were applied separately at a ratio of 5 L each with 500 L of water in a Knapsack sprayer per hectare and well shaken to create a homogenous solution. The Bio follows.A week prior to planted, early in the morning, the entire experimental plot was sprayed with a Bio.SoilZ water mixture when the soil was moist. In order to improve nutrient uptake, Bio.PlantZ was also sprayed on the crop's stem and leaves during the tillering stage when the leaves were active.

Figure 9: field follow up (Source: own photo)

Data to be collected.

Throughout the cropping season, data on tef yield and yield components was gathered. Among the data that was gathered were basic soil parameters (pH, SOC, texture, CEC, total N, and accessible P), initial composite soil samples from the study sites. Teff-specific factors such the number of productive tillers per plant, plant height, panicle length, grain and biomass yield, harvest index (HI), and fertilizer prices (local market prices) are determined by its primary yield.

Figure 10: field day at vegetative stage with highest rank agricultural officials (source: own photo)

Data analysis

Analysis of variance (ANOVA) was conducted on all recorded and gathered data using standard data analysis procedures (R software). The least significant difference (LSD) at the 5% significant level was used to compare the means of treatments.

Economic Analysis

The economic viability of using Bio.SoilZ and Bio.PlantZ stimulant for teff production was assessed using the partial budget analysis established by CIMMYT (CIMMYT, 1988). In the partial budget analysis, farm gate prices for the purchase of NPS, urea, Bio.SoilZ, and Bio.PlantZ stimulant, as well as the labor expenses associated with their application, were taken into account as total variable costs (TVC). Any average open market price kg-1 (130 and 12 ETB, respectively) was used to value the teff grain and its straw yield.

The price of urea and NPS fertilizers was deducted from the current market price, and the prices of each 1-liter Bio.SoilZ and 1-liter Bio.PlantZ stimulant (300.00 ETB each) were considered. The labor costs per person per day for a hectare of land were also considered when applying teff chemical fertilizer and spraying fresh stimulants. Prior to computation, teff grain and straw yields were reduced by 10% to reflect the true yield that could be achieved under farmers' production methods. In this study, a minimum acceptable rate of return of 100% or higher was required to declare profitability. To choose profitable treatments from the range investigated, the dominance analysis process described in CIMMYT (CIMMYT, 1988) was applied. When calculating the marginal rate of return (MMR), two non-dominated treatments are listed in ascending order of net benefit. MMR stands for return per unit of investment in the field management changes tested in the field experiment. The residuals were used to further verify the findings of the marginal analysis. The rate of return that farmers need, or the minimal return multiplied by the total variable costs, is subtracted from the equivalent net benefits to determine the residuals. Since the farmers had never used the combination of field management techniques investigated in this study, 100% of them are thought to have changed their practices (CIMMYT, 1988). Farmers are advised to use the treatments with the largest residuals after the analysis.

3. Results and Discussion

3.1. Pre-sowing soil physical and Chemical Properties of the experimental sites

The physico-chemical characteristics of the soils in experimental sites prior to sowing are shown in Table 3. Table 3 shows the initial status of soil properties. The findings indicated that the soil has a silt loam texture, is mildly alkaline, and has low levels of OC, OM, and total N.

Table 8: initial status of soil properties the experimental sites

Sites	Soil Texture (%)			Textural Class	pH	EC (ds m-1)	Ava.P (ppm)	OC (%)	OM (%)	TN (%)	CEC Cmol(+) /kg
	Sand	Silt	Clay								
1	18.6	66.4	15	Silt Loam	8.3	0.4	12.1	1.1	1.8	0.1	44.40
2	22.6	56.4	21	Silt Loam	7.9	0.3	19.4	0.8	1.4	0.1	34.80
3	28.6	54.4	17	Silt Loam	7.6	0.2	12.9	1.2	2.0	0.2	34.20
Means	23.3	59.1	17.7	Silt Loam	7.9	0.3	14.8	1.0	1.8	0.1	37.8
Status				suitable	MA	M	Medium	Low	Low	Low	High
Reference					lones, 2003)	(Peverill , 1999)	Cottenie, 1981)	(Tadesse, *et al.*, 1991)	(Tadesse, *et al.*, 1991)	(Debele , 1982)	(Landon , 2014)

Where, pH-power of hydrogen, EC- electric conductivity, OC- organic carbon, TN-total nitrogen, Ava.P- available phosphorus, CEC- cation exchange capacity, L- loam, C-clayey, CL-clay loam

3.2. Effect of Bio.SoilZ and Bio.PlantZ rates on Yield and Yield Components of tef

Day to 50% heading and days to 90% physiological maturity

The days to 50% heading and days to 90% heading were not significantly affected by the Bio.SoilZ and Bio.PlantZ bio-stimulate rates, according to the ANOVA results (Table 4). However, the control group had the longest days to 50% heading (54.11 days) of tef. The plot that received 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage had the shortest days to 50% heading (50.6 days). Additionally, the control group's delayed day to 90% physiological maturity (91.11 days) was noted. The plot that got T4 (100% RNP + 10L BSZ at sowing + 10L BPZ at vegetative stage) and T2 (100% RNP) had the shortest time to reach 90% physiological maturity (85.11 days).

Table 9: Combined results on Days to 50% Heading (DH), Days 90% Physiological Maturity (DPM), Plant Height (PH), Heading Length (HL), and No of Tillers (NT).

Treatments	DH (Days)	DPM (Days)	PH (cm)	PL (cm)	NT (#)
1) Negative Control	54.11^{a}	91.11^{a}	66.22^{d}	29.33^{f}	1.17^{d}
2) 100% RNP	49.00^{a}	85.11^{b}	90.52^{ab}	37.80^{abc}	1.77 ^{ab}
3) 100% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	49.56^{b}	85.44^{b}	93.98 ^{a}	38.46^{ab}	1.85^{a}
4) 100% RNP + 10L BSZ at sowing + 10L BPZ at vegetative stage	50.66^{ab}	85.11^{b}	90.26^{ab}	38.37^{ab}	1.75^{abc}
5) 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage	48.88^{b}	85.44^{b}	94.58^{a}	39.62^{a}	1.84^{a}
6) 75% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	50.33^{ab}	85.66^{b}	88.93^{ab}	35.93^{bcd}	1.68^{abc}
7) 50% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	51.33^{ab}	87.00^{ab}	85.42^{b}	35.55^{cd}	1.51^{bc}
8) 25% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	52.22^{ab}	87.66^{ab}	79.13^{c}	33.48^{de}	1.44^{cd}
9) 5L BS at sowing + 5L BPZ at vegetative stage	53.77^{a}	90.55^{a}	70.88^{d}	31.37^{ef}	1.46^{bcd}
MEAN	51.09	87.01	84.44	35.55	1.61
CV	8.06	5.02	7.30	7.59	21.68
LSD	NS	NS	5.83	2.55	0.331
P-value	0.067	0.134	<.0001	<.0001	0.0014

Where, means followed by the same letters are not significantly different (P≤0.05). DH- days to 50% heading, DM- days to 90% physiological maturity, PH- plant height, PL- panicle length, NT- no of tillers, CV-coefficient of variance, LSD- least significant difference

Plant Height

The Bio.SoilZ and Bio.PlantZ biostimulant rates had a substantial (P<0.0001) impact on plant height, according to the ANOVA result (Table 4). As a result, plots that received T5 (100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage) and T3 (100% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage) had the highest plant heights, measuring 94.58 and 93.98 cm, respectively, while the plot that received the negative control had the lowest plant height, measuring 66.22 cm (Table 4). Since nitrogen is essential to the structure of chlorophyll, the rise in plant height with increasing NPS fertilizer may be explained by an adequate supply of nutrients, which in turn led to greater vegetative development (Dereje *et al*, 2024).

Panicle Length

One of the yield components that affects grain yield is panicle length. Higher heading length crops may produce more grain (Dereje *et al.*, 2024). The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had a significant (P<0.0001) effect on heading length, according to the ANOVA results (Table 4). Therefore, the plot that received T5 (100% RNP + 20L BSZ at Sowing + 20L BPZ at vegetative stage) had the highest heading length (39.62 cm), but this treatment did not significantly differ from other treatments such as T4, T3, and T2, and the plot that

received the negative control had the lowest heading length (29.33 cm) (Table 4). Therefore, increased photosynthetic productivity and the buildup of high dry matter arise from the application of balanced fertilizer and efficient nutrient use, which in turn increases panicle length and the yield of grains (Fayera *et al.*, 2014).

Number of Tiller's

The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had a significant (P<0.0014) effect on the number of tillers, according to the ANOVA results (Table 4). Accordingly, the plot that received T3 (100% RNP + 5L BSZ at Sowing + 5L BPZ at Vegetative stage) had the most tillers (1.85), while the plot that received negative control had the fewest tillers (1.17) (Table 4).

Number of effective tillers

The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had a significant (P<0.0001) effect on the number of effective tillers, according to the ANOVA results (Table 5). Accordingly, the plot that received T2 (100% RNP) had the greatest number of effective tillers (1.71), whereas the plot that received negative control had the lowest number (1.14) (Table 5).

Straw yield

The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had significant (P<0.0001) effect on straw yield, according to the ANOVA data (Table 5). Accordingly, the plot that received T5 (100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage) had the maximum straw yield (4955.6 kg ha-1), while the plot that received negative control had the lowest straw yield (2000 kg ha-1) (Table 5).

Biomass Yield

The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had a significant (P<0.0001) effect on straw yield, according to the ANOVA data (Table 5). Accordingly, the plot that received T5 (100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage) had the maximum biomass yield (7000.0 kg ha-1), while the plot that received negative control had the lowest yield of biomass (2744.4 kg ha-1) (Table 5). The availability of macronutrients and certain secondary nutrients combined with the NPS fertilizer may have contributed to the notable increase in biomass output by raising vegetative and, in turn, biomass yield (Dereje *et al.*, 2024).

Table 10: Combined result of No of Effective Tillers, Biomass Yield, Grain Yield and Harvesting Index

Treatments		NET (no)	SY (kg ha^{-1})	BY (kg ha^{-1})	GY (kg ha^{-1})	HI (%)
1)	Negative Control	1.14^{e}	2000.0d	2744.4^{d}	744.4^{d}	25.37
2)	100% RNP	1.71^{a}	4677.6ab	6477.6^{a}	1800.0^{ab}	27.93
3)	100% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	1.65^{ab}	4838.8a	6699.9^{a}	1861.1^{a}	27.78
4)	100% RNP + 10L BSZ at sowing + 10L BPZ at vegetative stage	1.60^{ab}	4837.8a	6711.1^{a}	1873.3^{a}	28.61
5)	100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage	1.64^{ab}	4955.6a	7000.0 ^{a}	2044.4 ^{a}	29.10
6)	75% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	1.44^{bcd}	4575.6ab	6322.2 ^{ab}	1746.7 ^{ab}	27.98
7)	50% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	1.46^{bc}	4044.4b	5577.8 ^{b}	1533.3^{bc}	27.02
8)	25% RNP + 5L BSZ at sowing + 5L BPZ at vegetative stage	1.24^{de}	3088.9c	4333.3 ^{c}	1244.4 ^{c}	27.50
9)	5L BS at sowing + 5L BPZ at vegetative stage	1.27^{cde}	2222.2d	3066.7^{d}	844.4d	26.25
MEAN		1.46	3915.64	5437	1521.35	27.50
CV		15.67	20.48	16.63	20.80	16.51
LSD		0.217	758.63	855.59	299.44	NS
P-value		<.0001	<.0001	<.0001	<.0001	0.7911

Where, means followed by the same letters are not significantly different (P≤0.05), NET- no of effective tillers, SY- straw yield, BY- Biomass yield, GY- Grain Yield, HI- Harvesting Index, CV-coefficient of variance, LSD- least significance difference.

Grain Yield

The Bio.SoilZ and Bio.PlantZ bio-stimulant rates had a significant (P<0.0001) effect on grain yield, according to the ANOVA data (Table 5). Accordingly, the plot that received T5 (100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage) produced the maximum grain yield (2044.4 kg ha-1), while the plot that received control produced the lowest biomass production (744.4 kg ha-1) (Table 5). Therefore, the research site's tef production is increased by 12% when Bio.SoilZ and Bio.PlantZ liquid fertilizers are applied. In a similar vein, applications of Bio.SoilZ and Bio.PlantZ can increase maize output by 20% and cotton yield by 30% when compared to mineral fertilizer application, according to data from the company's website (Fayera *et al.*, *et al.*, 2014). According to Wakjira's current findings, Tesfahun (2018) proposed that the transplanting method with 120 kg ha-1 NPS fertilizer produced the highest tef grain yield (3.77 t ha-1).

Harvesting Index

The harvesting index was not significantly (P>0.05) affected by the Bio.SoilZ and Bio.PlantZ bio-stimulant rates, according to the ANOVA results (Table 5). There was, however, a numerical difference between the treatment trials; the plot that received T5 (100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage) had the highest HI (29.1%), while the plot that received control had the lowest biomass yield (25.35%) (Table 5).

3.3. Correlation Between Phenological, Growth Parameter and Yield of Teff

Table 6 shows the correlation between the teff agronomic parameters. Plant height (r=0.711), heading length (r=0.499), number of effective tillers (r=0.42), and straw yield (r=0.906) all showed favorable correlations with tef grain yield. This suggests that when plant height, heading length, number of effective tillers, and straw yield rise, grain yield increases dramatically. On the other hand, days to 50% heading (r=-0.2405) and days to 90% physiological maturity (r=-0.0063) had a negative correlation with grain yield. This result was consistent with the findings of Getahun *et al.* (2018), who discovered a negative correlation between grain yield and both maturity (r=-0.39) and days to heading (r=0.16).

Economic analysis

The fertilizer application of 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage produced the largest net benefit (274,389.5 ETB ha-1) and the highest marginal rate of return (MRR) (185.76%), according to partial budget analysis. Unfertilized plots yielded the lowest net benefit (111094.8 ETB ha-1) (Table 7). In comparison to 100% RNP, which had an MRR of 31.78 ETB for 1.00 ETB investment, the MRR showed that tef growers might receive an additional 1.86 ETB for 1.00 ETB investment in the application of liquid fertilizer at the rate of 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage.

As a result, Tahtay Koraro District was advised to use this procedure for the production of tef since it was more economically advantageous. The residuals were used to further verify the marginal analysis results (Table 7). The rate of return that farmers need, or the minimal return multiplied by the total variable costs, is subtracted from the equivalent net benefits to determine the residuals. As a result, the highest MRR was determined to be the first rank.

Table 6: Correlation Between Phenological, Growth Parameter and Yield of Tef

	Loc	Tret	HD	MD	PH	HL	NT	NET	SY	BY	GY	HI
HD	0.06310	0.10922	1.00000									
P-value	0.5758	0.3318										
MD	-0.39084	0.07087	0.34598	1.00000								
P-value	0.0003	0.5295	0.0016									
PH	-0.24527	-0.12103	-0.33445	-0.17385	1.00000							
P-value	0.0273	0.2818	0.0023	0.1206								
HL	0.05482	-0.12388	-0.29744	-0.24161	0.85589	1.00000						
P-value	0.6269	0.2705	0.0070	0.0298	<.0001							
NT	0.15132	-0.06519	-0.18917	-0.16701	0.45053	0.54094	1.00000					
P-value	0.1775	0.5631	0.0908	0.1362	<.0001	<.0001						
NET	0.07944	-0.21101	-0.23954	-0.22249	0.50320	0.49632	0.56491	1.00000				
P-value	0.4809	0.0586	0.0313	0.0459	<.0001	<.0001	<.0001					
SY	-0.45495	-0.16654	-0.24614	-0.11289	0.68902	0.50180	0.30953	0.40637	1.00000			
P-value	<.0001	0.1373	0.0268	0.3156	<.0001	<.0001	0.0049	0.0002		<.0001		
BY	-0.51240	-0.16412	-0.25467	-0.08393	0.72500	0.52194	0.29309	0.42910	0.98297	1.00000		
P-value	<.0001	0.1432	0.0218	0.4563	<.0001	<.0001	0.0079	<.0001	<.0001			
GY	-0.57643	-0.13680	-0.24052	-0.00631	0.71160	0.49906	0.21650	0.42447	0.81365	0.90661	1.00000	
P-value	<.0001	0.2233	0.0305	0.9554	<.0001	<.0001	0.0522	<.0001	<.0001	<.0001		<.0001
HI	-0.40503	0.00058	-0.12508	0.09166	0.35725	0.21068	-0.01306	0.14251	0.08700	0.25741	0.61465	1.00000
P-value	0.0002	0.9959	0.2659	0.4158	0.0011	0.0590	0.9079	0.2044	0.4400	0.0203	<.0001	

Where, DH- days to 50% heading, DM- days to 90% physiological maturity, PH- plant height, HL- heading length, NT- no of tillers NET- no of effective tillers, SY- straw yield, BY- Biomass yield, GY- Grain Yield, HI- Harvesting index

Table 7: Dominance analysis effect of Bio.SoilZ and Bio.PlantZ liquid fertilizer on teff production

Tr	Adjected GY kg ha^{-1}	Straw yielc kg ha^{-1}	TVC (ETB)	Revenue from grain (ETB)	Revenue from Straw (ETB)	Total Revenue	Net benefit (ETB)	Marginal Cost	Marginal Benefit	Marginal Rate of Return
T1	669.96	2000	0	87094.8	24000	111094.8	111094.8	0	0	0.00
T2	759.96	2222.2	3750	98794.8	26666.4	125461.2	121711.2	3750	10616.4	283.10
T3	1119.96	3088.9	6068.12	145594.8	37066.8	182661.6	176593.5	2318.12	54882.28	2367.53
T4	1379.97	4044.4	8386.23	179396.1	48532.8	227928.9	219542.7	2318.11	42949.19	1852.77
T5	1620	4677.6	9572.49	210600	56131.2	266731.2	257158.7	1186.26	37616.04	3170.98
T6	1572.03	4575.6	10704.35	204363.9	54907.2	259271.1	248566.8	1131.86	-8591.96	D
T7	1674.99	4838.8	13022.49	217748.7	58065.6	275814.3	262791.8	2318.14	14225.06	613.64
T8	1685.97	4837.8	16772.49	219176.1	58053.6	277229.7	260457.2	3750	-2334.6	D
T9	1839.96	4955.6	24272.49	239194.8	59467.2	298662	274389.5	7500	13932.3	185.76

Where, Tr-Treatments, TVC- Total Variable Cost,T1-Negative Control,T2-5L BS @Sowing + 5L BPZ @ vegetative stage, T3-25% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage, T4- 50% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage, T5- 100% RNP,T6- 75% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage, T7- 100% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage,T8- 100% RNP + 10L BSZ @Sowing + 10L BPZ @ vegetative stage, T9- 100% RNP + 20L BSZ @Sowing + 20L BPZ @ vegetative stage

Table 8: Residual analysis effect of Bio.SoilZ and Bio.PlantZ liquid fertilizer on teff production

Treatments	Total Variable Cost (ETB)	Net benefit (ETB)	Marginal Cost	Marginal Benefit	Marginal Rate of Return	Mini rate of return (100% *TVC)	Residual	Rank residual
5L BS @Sowing + 5L BPZ @ vegetative stage	3750	121711.2	3750	10616.4	283.10	3750.00	117961.20	6
25% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage	6068.12	176593.5	2318.12	54882.3	2367.53	6068.12	170525.36	5
50% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage	8386.23	219542.7	2318.11	42949.2	1852.77	8386.23	211156.44	4
100% RNP	9572.49	257158.7	1186.26	37616	3170.98	9572.49	247586.22	3
100% RNP + 5L BSZ @Sowing + 5L BPZ @ vegetative stage	13022.5	262791.8	3450	5633.1	163.28	13022.49	249769.32	2
100% RNP + 20L BSZ @Sowing + 20L BPZ @ vegetative stage	24272.5	274389.5	11250	11597.7	103.09	24272.49	250117.02	1

4. Conclusion and Recommendations

When Bio.SoilZ and Bio.PlantZ stimulant rates are used in conjunction with prescribed NP fertilizer, the main agronomic parameters of teff can be improved compared to control and small dose liquid fertilizer alone. Days to heading and days to physiological maturity were not significantly ($P>0.05$) affected by the trial, according to the analysis of variance. In contrast, the statistical analysis of variance revealed that the recommended NP fertilizer and Bio.SoilZ and Bio.PlantZ stimulant rates significantly ($P<0.05$) affected plant height, heading length, number of tillers, number of effective tillers, straw yield, biomass yield, and grain yield. The application of 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage produced the highest plant height (94.58 cm), heading length (39.62 cm), straw yield (4955.6 kg ha-1), biomass yield (7000 kg ha-1), and grain yield (2044.4% kg ha-1). The field unfertilized plot and a plot that received a small dose of Bio.SoilZ produced the lowest values, and the Bio.PlantZ stimulant rates were significantly lower than those of all other treatments. Additionally, the study district benefited economically from the use of 100% RNP + 20L BSZ at sowing + 20L BPZ at vegetative stage for teff production, according to the partial budget analysis. Therefore, the following set of guidelines is recommended in order to use Bio.SoilZ and Bio.PlantZ stimulants in a sustainable manner:

- More studies on farm trials at permanent plots with various soil and crop types should be carried out.
- In a similar vein, studies on its long-term residual effects on soil health and quality should be carried out.
- Since the study was conducted in conjunction with the suggested NP fertilizer, more research should be conducted at different rates of Bio.SoilZ and Bio.PlantZ in order to investigate the separate effects of these stimulants.

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Drainage Lysimeter-Based Measurement of Evapotranspiration and Crop Coefficient of Haricot Bean under the Semi-arid Climate of Melkassa, Ethiopia

Tatek Wondimu Negash* Gobena Dirirsa Bayisa and Abera Tesfaye Tefera

Melkassa Agricultural Research Center (MARC), Ethiopian Institute of Agricultural Research (EIAR)
P.O. Box 436, Adama, Ethiopia
*Corresponding author: tatek.wondimu456@gmail.com

Abstract

Haricot bean is an important economic crop widely grown in Ethiopia. This study aimed to determine actual crop evapotranspiration (ETc) and crop coefficient (Kc) values for haricot bean using field measurements. The experiment was conducted during the 2017 and 2018 cropping seasons at the Melkassa Agricultural Research Center, Ethiopia. Actual crop evapotranspiration and crop coefficients were determined using non-weighing lysimeters. Reference evapotranspiration (ETo) was estimated using the FAO Penman–Monteith method, while actual crop evapotranspiration was calculated using the soil water balance approach. Crop coefficient values were derived as the ratio of measured ETc to ETo. The seasonal actual crop evapotranspiration of haricot bean was 493.0 mm in 2017 and 410.1 mm in 2018, with a two-year average of 451.6 mm. The mean locally developed crop coefficient values at the initial, mid-season, and end-season growth stages were 0.50, 1.16, and 0.67, respectively. The average FAO-adjusted Kc values over the two years were 0.41 at the initial stage and 1.14 at mid-season. Locally developed and FAO-adjusted crop coefficient values showed only marginal differences. These findings provide valuable information for improving irrigation water management of haricot bean in the region. Developing location-specific crop coefficient values for different growth stages is crucial for enhancing water-use efficiency, optimizing irrigation scheduling, and supporting sustainable haricot production in semi-arid environments.

Keywords: Field-based hydrological assessment, Growth-stage water demand, Irrigation water management, Soil water balance, Water-use efficiency

1. Introduction

Ethiopia grows haricot beans, a significant commercial crop, at elevations ranging from 1400 to 2000 meters above sea level (Wasae, 2021). It makes up 9.5% of all agricultural exports and is the third most valuable commodity, behind coffee and sesame (Ephrem, 2016). The Middle Rift Valley of Ethiopia produces around 60% of the country's haricot beans, according to Laike *et al.* (2006). In many regions of Eastern and Southern Africa, particularly Ethiopia, the crop is a vital food crop (Katungi *et al.*, 2009). It is the second most important cash crop after tef and is grown by farmers during periods of sporadic rainfall (CSA, 2016).

For Ethiopian smallholder farmers, haricot beans are a significant source of income and protein (Murut *et al.*, 2014; Fentie *et al.*, 2024). They also aid in fixing nitrogen in the soil (Kebede, 2020). Ethiopia produces 1.72 tons of haricot beans per hectare on average (CSA, 2016). However, each variety has a different yield potential. The yield performance of four haricot bean varieties—Awash-Melka: 2.07 tons/ha (irrigation) and 1.9 tons/ha (rainfed); Awash-1: 2.3 tons/ha (irrigation) and 1.65 tons/ha (rainfed); Mexican-142: 2.05 tons/ha

(irrigation) and 1.65 tons/ha (rainfed); Argen: 1.56 tons/ha (irrigation) and 1.7 tons/ha (rainfed); Chore: 2.45 tons/ha (irrigation) and 1.96 ha/ton (rainfed) were reported by Murut *et al.* (2014).

The authors draw the conclusion that all varieties produced their highest yield when irrigation was used. This results from providing the crop with the appropriate amount of water in accordance with its requirements. Water should be applied in accordance with the crops' evapotranspiration requirements to increase agricultural productivity. Therefore, understanding actual crop evapotranspiration (ETa) is crucial to increasing production, quality, and efficiency of water use.

Both weighing and non-weighing lysimeters can be used to measure the ETa using the soil water balance technique. One tool for measuring the main elements of the hydrological water balance is a lysimeter. Irrigation systems can be managed and planned using a non-weighing-type lysimeter that measures long-term ETc on a weekly, decadal, and monthly basis (Allen *et al.*, 1998). ETa levels can be measured for brief periods of time using a weighing-type lysimeter (Srinivas and Tiwari, 2018). Therefore, this study's primary goal was to use non-weighing lysimeters to evaluate the haricot bean's daily, seasonal, and peak evapotranspiration rates.

The reference evapotranspiration has been calculated using a variety of methods. The initial ETo equation was presented by Penman in 1948 and later modified by several different scholars (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985; Allen *et al.*, 1998). The only standardized method that can produce acceptable ETo results in a variety of climatic conditions is the modified FAO-56 Penman-Monteith methodology. Therefore, the second goal of this study was to use daily climatic data to drive the daily, seasonal, and peak reference evapotranspiration (ETo).

Additionally, a two-step technique that links the crop-specific coefficient Kc to ETo can be used to estimate the ETa. Technicians and irrigation professionals typically use this approach in real-world situations since it is very practical for calculating ETa. However, when using measured ETc, the crop coefficient (Kc) is required to make irrigation planning easier. The Kc is a popular indication of agricultural water requirements and represents the crop's unique water consumption, which fluctuates throughout the growing season due to physiological changes in the crop (Allen *et al.*, 1998). It is calculated using the ratio of ETa to ETo. Standard Kc values for various crops were reported by Doorenbos and Pruitt (1977) and Allen *et al.* (1998) and subsequently updated by Pereira *et al.* (2021). Nevertheless, the reported Kc values differed significantly from the site-specific Kc values. Hence, those authors underlined the importance of developing kc values for each crop based on lysimeter and local climatic data. Other researchers reported the haricot bean crop coefficient (Kc). Laike *et al.* (2006) reported a haricot bean crop coefficient (kc) of 0.34 at the initial stage, 0.7 at the development stage, 1.01 at the mid-stage, and 0.68 at the late stage in the semi-arid area of Melkassa, Ethiopia. In an arid region of northern Egypt, El-Noemani *et al.* (2015) found that the Kc values of haricot beans varied from 0.63 to 0.64 at the beginning, 0.87 to 0.82 during development, 0.99 to 1.09 during midseason, and 0.80-0.95 during harvest. The significance of creating Kc values for every crop based on lysimeter and local climate data was emphasized by those authors. For significant cash crops like the haricot bean during the warm cropping season in Ethiopia's semi-arid climate, the Kc based on lysimeter studies has

not been developed. Therefore, the final goal of this study was to determine the Kc values for haricot beans utilizing daily ETo and measured ETc data for local irrigation planning and control.

2. Materials and Methods

2.1. Study area

The Melkassa Agricultural Research Center in Ethiopia (8° 24′ 53′ N, 39° 19′ 40′ E) was the site of the field study (Fig. 1). With erratic and uneven rainfall patterns, the climate was classified as semi-arid. The average minimum and maximum temperatures throughout the long period (1977–2018) ranged from 13.8 ºC to 28.7 ºC. Over the same time period, the region received 825 mm of rain on average annually. The months with the most rainfall were July, August, and September. The region's mean annual wind speed and ETo ranged from 0.3 to 2.71 m s-1 and 3.8 to 5.42 mm day-1, respectively, between 1977 and 2018 (Authors). Fig. 2 shows the monthly climate factors for the 2017 and 2018 haricot bean growth season. The study area's soil was classified as clay loam soil texture. The soil's permanent wetting point (PWP) was 0.22 m3 m-3, its field capacity (FC) was 0.32 m3 m-3, and its bulk density was 1.13 g cm-3.

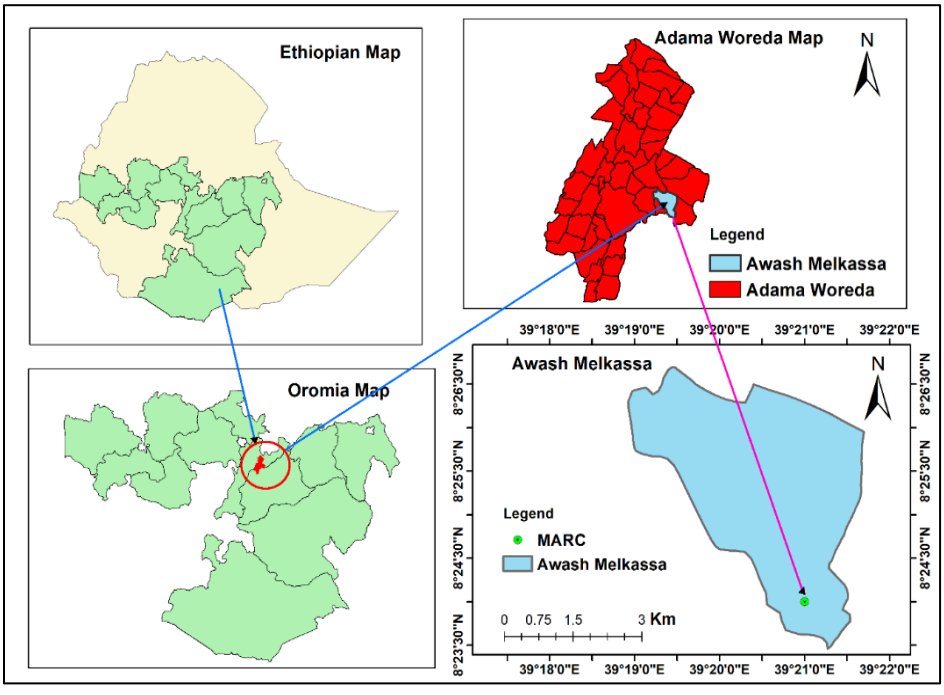

Figure 11: Study Area Map

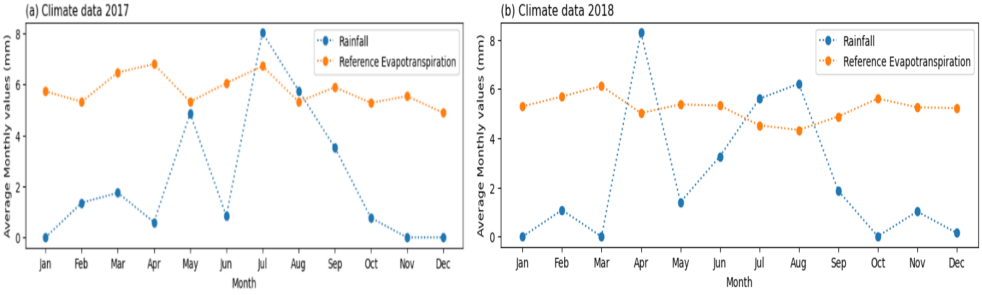

Figure 12: Average monthly climate data during (a) 2017 and (b) 2018 haricot bean experimental period.

2.2. The Experimental Setup

The haricot bean's ETc and Kc were measured using two lysimeters. The internal planting area of the first lysimeter was 2 m2, while that of the second lysimeter was 4 m2. With a 1 m effective soil depth, an additional 1 m layer, 0.2 m of rock, 0.2 m of gravel, and 0.2 m of sand pack beneath, the lysimeters' total depth was 2.6 m. With the internal space included, the lysimeter's overall area was 36 m2 (6 × 6 m). Each lysimeter's access chamber was connected to an underground steel conduit to drain the extra water. To keep surface runoff out of the lysimeter on wet days, the rims were positioned 0.1 meters above the soil's surface. To track the soil moisture levels inside the lysimeters, access tubes were placed to an effective root depth of one meter.

2.3. Crop Agronomic Practice

On clay loam soil, the haricot bean variety Awash Melka was cultivated for two consecutive cropping seasons in 2017 and 2018. In and out of the lysimeter regions, the seeds were sowed in February 2017 and March 2018. The two lysimeters were made to have the same moisture content prior to seeding. For the haricot bean, 60 cm was the spacing between rows, and 10 cm was the spacing within rows. The lysimeter and its surroundings were regularly treated with all advised agronomic techniques (fertilization, weed control, pest control, etc.). For haricot beans, a fertilizer rate of 50 kg ha-1 urea and 100 kg ha-1 diammonium phosphate (DAP) is advised. Therefore, 360 grams of diammonium phosphate (DAP) and 180 grams of urea were utilized during planting for each lysimeter. A split rate was used to apply the urea. About 30 days after seeding, on March 22, 2017, and April 5, 2018, 180 g of urea were applied a second time. The haricot bean harvests were harvested during two consecutive experimental seasons, about 100 days following seeding. When two weeks remained till harvest, the crop's watering was stopped.

2.4. Irrigation Application and Soil Moisture Monitoring

The lysimeter was used to measure the soil water content before and after each irrigation, and irrigation events were scheduled according to the degree of soil moisture depletion. The soil water content was measured using gravimetric (oven) and neutron moisture meter (CPN503) techniques at depths of 0 to 15 cm and 15 to 100 cm, respectively. The Bouyoucos hydrometer method was used to measure the soil texture (the percentage of sand, silt, and clay) or particle size distribution. To determine the soil bulk density in the experimental field, undisturbed soil samples were collected using the core method. After measuring the soil

moisture at the FC and PWP with a pressure-plate device, the total accessible soil water can be calculated by deducting the permanent wilting point (PWP) from the field capacity (FC). When the roots layer had lost roughly 45% of the available soil water, the crop was given irrigation water. Applying a predetermined amount of irrigation water to crops is possible with a watering. When the crops reached maturity, irrigation was stopped. The amount of irrigation water applied to the crop is calculated using Equation (1).

$$\text{Quantity of applied water } (m^3) = \text{Lysimeter area } (m^2) * \text{Applied depth } (m) \quad (1)$$

2.5. Actual Crop Evapotranspiration (ETc) and Reference Evapotranspiration (ETo)

The FAO Penman-Monteith equation was used to calculate daily ETo using the Cropwat 8.0 model. Weather data, such as daily minimum and maximum air temperature, wind speed at a height of two meters, relative humidity, and daylight hours, were used as model inputs. The crops' ETa was calculated daily using Equation (2). Equations 3 and 4 of the reliable rain technique were used to compute the effective rainfall, which was the portion of the rainfall that fell on the soil and became accessible for crops in millimeters. This is because it was created using assessments of several semi-arid climates.

$$ETa = \left[\frac{I + P_{eff} - D \pm \Delta S}{\Delta t}\right] \quad (2)$$

where, ETa = actual crop evapotranspiration (mm day^{-1}), P_{eff} = effective rainfall (mm), I = applied irrigation depth (mm), ΔS = change in soil moisture (mm), D = drainage depth (mm), and t = time between two consecutive observations in days.

The drainage depth (D) in the underground room was measured using a graded cylindrical tube. By deducting the moisture content obtained today from the moisture content obtained yesterday, changes in soil moisture (ΔS) were computed.

$$P_{eff} = (0.6 * P) - \frac{10}{3} \quad \text{for } P_{month} \leq 70 \text{ mm} \quad (3)$$

$$P_{eff} = (0.8 * P) - \frac{24}{3} \quad \text{for } P_{month} > 70 \text{ mm} \quad (4)$$

where P_{eff} is effective rainfall (mm) and P is the total precipitation in the crop growing season (mm).

2.6. Crop Coefficient (Kc)

The Kc signifies the effect of the crop on water consumption, which varies throughout the growing stages, attributable to physiological changes in the crop. Eq. (5) was used to compute the stage-wise haricot bean Kc values:

$$Kc = \frac{ETa}{ETo} \quad (5)$$

Where: Kc is the crop coefficient (dimensionless); ETa is actual crop evapotranspiration (mm day^{-1}), and ETo is reference evapotranspiration (mm day^{-1}).

2.7. Adjustment of FAO Crop Coefficient Using Local Climate

The Kc values for haricot beans in FAO-56 are 0.4, 1.15, and 0.35 for the first, middle, and end seasons, respectively. These figures were calculated with wind speed (u2) = 2 m s-1 and average relative humidity (RHmin) = 45%. The local climate, where wind speed and RHmin vary by 2 m s-1 and 45%, respectively, requires these figures to be adjusted. The Kc values greater than 0.45 for the mid and end seasons were adjusted to account for the climatic conditions of the area and plant height as follows (Allen *et al.*, 1998):

$$\mathrm{Kc}_{\mathrm{mid/end-FAO}} = \mathrm{Kc}_{\mathrm{mid/end}}\,(\mathrm{Tab}) + [0.04\,(u_2 - 2) - 0.004\,(\mathrm{RH}_{\mathrm{min}} - 45)] * (h/3)^{0.3} \quad (6)$$

where $\mathrm{Kc}_{\mathrm{mid/end-FAO}}$ = FAO-adjusted Kc for the mid/end-season, $\mathrm{Kc}_{\mathrm{mid}}\,(\mathrm{Tab})$ = Kc tabulated for the mid/end-season gained from FAO-56, u_2 = Mean wind speed at 2 m height during the mid/end season (m s^{-1}), RHmin = Mean relative humidity during the mid/end season (%), and h = Mean plant height during the mid/end season (m). The initial crop coefficient for the haricot bean was adjusted using the calibration methodology presented by (Allen *et al.*, 1998).

3. Results and Discussion

3.1. Actual Crop Evapotranspiration and Reference Evapotranspiration

Table 1 displays the haricot beans' seasonal actual evapotranspiration (ETa) and derived hydrological water balance components (mm). Figure 3a–d displays the average daily real crop evapotranspiration (ETa) and reference evapotranspiration (ETo) for the haricot bean experimental periods in 2017 and 2018. For agricultural fields to manage irrigation water, precise ETa measurements based on crop development stage, root depth, soil water-holding capacity, and precipitation data are crucial.

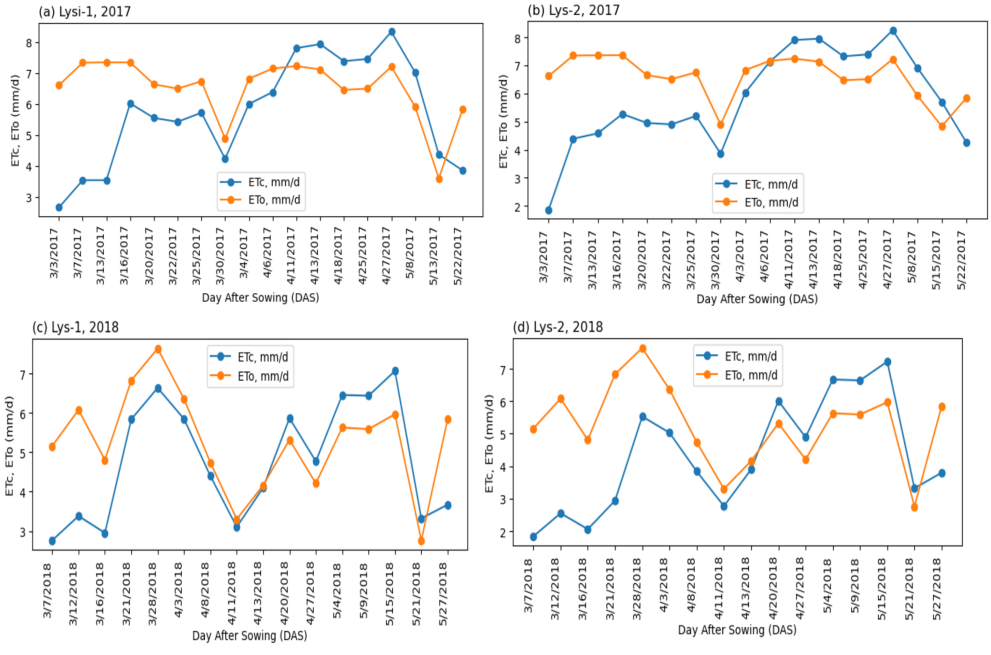

Figure 13: ETa, ETo as a Function of Days After Sowing for haricot bean.

Table 11: Hydrological water balance components (mm) for haricot bean during the 2017 and 2018 experimental seasons.

Lysimeter -1 (2 m^2)								**Lysimeter-2 (4 m^2)**					**Average**				
Year			**2017**														
Stages	**Days**	**Peff**	**I**	**D**	**ΔS**	**Eta**	**ETo**	**I**	**D**	**ΔS**	**ETa**	**ETo**	**I**	**D**	**ΔS**	**ETa**	**ETo**
Initial	19	-	63.4	0.2	3.7	59.5	133.1	58.9	1.9	-4.8	61.8	133.1	61.2	1.0	-0.6	60.7	133.1
Development	24	24.6	121.9	11.2	2.4	132.9	155.2	186.3	83.1	-2.9	130.7	155.2	154.1	47.2	-0.2	131.8	155.2
Mid-season	37	55.0	201.2	28.0	-32.1	260.3	226.1	244.9	52.0	-28.3	276.2	241.9	223.1	40.0	-30.2	268.3	234.0
Late-season	20	9.8	25.0	-	-	34.8	52.6	20.0	-	-	29.8	40.9	22.5	-	-	32.3	46.7
Total	100	89.4	411.5	39.4	-26.0	**487.5**	**567.0**	510.1	137.0	-36.0	**498.5**	571.1	460.8	88.2	-31.0	**493.0**	**569.0**

Lysimeter -1 (2 m^2)								**Lysimeter-2 (4 m^2)**					**Average**				
Year			**2018**														
Stages	**Days**	**Peff**	**I**	**D**	**ΔS**	**ETa**	**Eto**	**I**	**D**	**ΔS**	**ETa**	**ETo**	**I**	**D**	**ΔS**	**ETa**	**ETo**
Initial	18	-	83.8	11	1.1	71.7	109.6	33.9	-	-11	44.87	109.6	58.84	5.5	-4.95	58.29	109.6
Development	23	85.9	75.4	47	-6	121.1	133.6	58.3	58.5	-18.5	104.2	133.6	66.86	52.75	-12.3	112.7	133.6
Mid-season	38	72.5	165.6	19	5.4	214.2	186.5	163	16.5	-0.7	219.4	186.5	164.2	17.75	2.35	216.8	186.5
Late-season	21	-	23	-	1	22	35.1	22.8	-	-	22.8	35.1	22.9	-	0.5	22.4	35.1
Total	100	158.4	347.8	77	1.5	**429**	464.7	278	75	-30.2	391.3	464.7	312.7	76	-14.4	**410.1**	**464.7**
Average over two years	100	123.9	379.7	58.2	-12.25	**458.2**	515.85	393.9	106	-33	**444.9**	517.89	387	82.098	-22.68	**451.6**	**516.9**

Note: Peff is effective rainfall (mm), I is applied irrigation (mm), and D is drainage depth (mm), ΔS is change in soil moisture (mm), ETa is actual crop evapotranspiration (mm day^{-1}), and ETo is reference evapotranspiration (mm day^{-1}).

3.2. Locally Measured and FAO Adjusted Haricot Bean Crop Coefficient (Kc)

The developed daily actual crop coefficient values for the haricot bean throughout the growing seasons of 2017 and 2018 are displayed in Figure 4. According to the findings, Kc levels started to rise in the beginning of the season, peaked in the middle, and then started to decline at the conclusion. This result aligned with the pattern reported for FAO-56. The Kc values in 2017 were 0.46-0.5 at the start of the season, 1.14-1.15 at the middle of the season, and 0.66-0.73 at the end. However, according to Table 2, the Kc values for the first, middle, and end seasons of 2018 were 0.41-0.64, 1.15-1.18, and 0.63-0.65, respectively. For the two experimental seasons, the average Kc values were 0.5, 1.16, and 0.67 at the beginning, middle, and conclusion of the season. The mid-season Kc values of the locally measured and FAO-adjusted haricot beans are displayed in Table 3.

Table 12: Measured Kc-Values for haricot bean during the 2017 and 2018 experimental periods.

Measured Kc			
Experimental Year	Kc-ini-measured	Kc-mid- measured	Kc-end- measured
2017	0.46-0.5	1.14-1.15	0.66-0.73
2018	0.41-0.64	1.15-1.18	0.63-0.65
Average Kc	**0.5**	**1.16**	**0.67**

Note: The Kc values for the development stage can be generated linearly from the initial and mid-stage values.

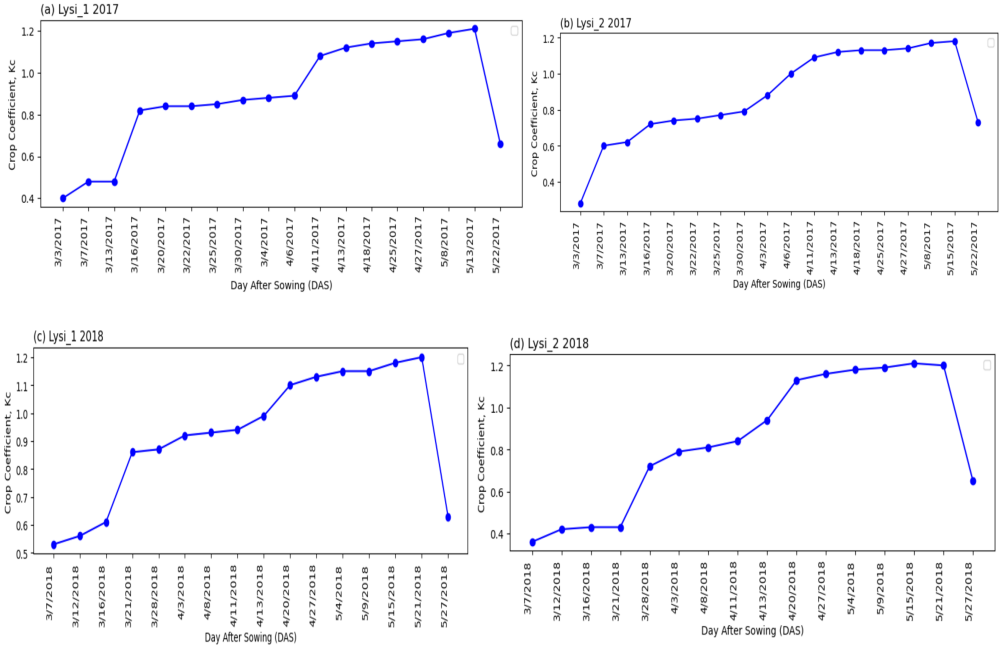

Figure 14: Crop Coefficient Vs. Days After Sowing for Haricot Bean in 2017 and 2018.

Table 13: FAO-adjusted and Measured Kc-values for haricot beans in the 2017 and 2018 experimental seasons.

Experimental Year	$Kc_{-ini-(measured)}$ $Kc_{-ini\ (adj)}$	$Kc_{-mid-(Measured)}$) $Kc_{-mid(adj)}$	$Kc_{-end-(Measured)}$ $Kc_{-end\ (adj)}$
2017	0.48 (0.35)	1.15 (1.16)	0.69 (**)
2018	0.525 (0.47)	1.17 (1.11)	0.64 (**)
Average Kc	0.5 (0.41)	1.16 (1.14)	0.76 (**)

Note: ** not adjusted Kc value because the FAO Kc end-season value is < 0.45. $Kc_{-mid(adj))}$ and $Kc_{-end(adj))}$ = FAO adjusted Kc values for mid and end-season, respectively, where wind speed and RH_{min} differ from 2 m s^{-1} and 45%; $Kc_{-mid-(Measured}$) and $Kc_{-end-(Measured)}$ = locally measured Kc values for mid and end-season, respectively.

ETa, ETo, and Kc values for haricot beans were assessed in this study during the 2017 and 2018 growing seasons. Understanding the water needs at various crop stages through these measures is essential for developing irrigation management plans. The findings demonstrated that ETa values differed depending on the stage of crop growth, including starting, development, mid-season, and end-season. The mid-season, when the haricot bean was developing at its fastest rate, had the largest water consumption (Table 1). Since water use is at its peak during this phase, this trend is crucial for irrigation planning. The average ETa was 493.0 mm in 2017 and 410.1 mm in 2018. Because of the increased rainfall in 2018, less irrigation was needed, resulting in lower values. Over the course of the two trial years, an average ETa value of 451.6 mm was noted (Table 1). The haricot bean seasonal actual crop evapotranspiration assessed in this study fell between 300 and 500 mm, as previously reported (Doorenbos and Kassam, 1979). The results of this study are also similar to those of Laike *et al.* (2006), who used a non-weighing lysimeter to report a haricot bean crop water requirement of 447.16 mm while doing research in Ethiopia's Central Rift Valley. According to Alipour *et al.* (2022), haricot beans in Afghanistan have a seasonal ETa value of 579 mm in non-stressful circumstances. The duration of the crop growth cycle and temperature variations caused by altitude may be the cause of this. Using full irrigation treatments, Otoro and Hatiye (2024) observed a haricot bean ETa value of 410 mm in the Arba Minch region of Southern Ethiopia.

A number of variables, including temperature, humidity, wind speed, and solar radiation, affect the atmosphere's evaporative demand, or ETo. A high ETo implies a high atmospheric water demand, which means crops lose more water through evapotranspiration and need more irrigation to sustain ideal growth. According to the study, the average seasonal ETo values were 464.7 mm in 2018 and 569.0 mm in 2017 (Table 1). Due to elements like greater temperatures and humidity, the higher ETo in

2017 indicates that atmospheric conditions were more demanding than in 2018. Higher rainfall in 2018 helped to lower ETo values since the soil's abundant moisture decreased the atmospheric demand for more water. These variances show how shifting weather patterns have a direct impact on irrigation requirements, necessitating modifications to guarantee crops get enough water efficiently.

The Kc values that link ETa to ETo in this study showed a normal trend, rising from the beginning to the middle of the season and falling toward the end. In 2017, for example, the Kc values were 0.46-0.5 at the beginning of the season, 1.14-1.15 at the middle of the season, and 0.66-0.73 at the end (Table 2). Similar patterns were noted in 2018, however there were some minor differences, such as a wider range in initial-stage Kc (0.41-0.64) because of fluctuating weather. This demonstrates that although Kc generally follows a trend, climate factors may cause it to differ. The obtained Kc values exceeded the FAO-adjusted values at every step (Table 3). The haricot bean Kc-mid values of 1.15 reported by Allen *et al.* (1998), Tasumi and Allen (2007), and 1.07 reported by Jabow *et al.* (2015) were lower than the average Kc-mid measured for this study. It demonstrated that crop water requirements were higher locally than the FAO reference values. This can be the result of particular crop traits and local climate circumstances. It implies that locally measured Kc values rather than FAO data can be used to deliver irrigation water with greater accuracy. Tables 2 and 3 provide the specifics of the haricot bean's locally measured and FAO-adjusted Kc-values.

4. Conclusion and Recommendations

The significance of creating crop evapotranspiration and crop coefficients for semi-arid locations is highlighted by this work. In irrigated agriculture, accurate water allocation is essential to achieving maximum crop yields and conserving water resources as water becomes more scarce owing to competition among sectors. While overestimating might result in excessive water application, which reduces the amount of water available for other applications, underestimating crop evapotranspiration may result in yield penalties due to water stress. Since Kc is a key component in calculating ETc for any crop, it is imperative to understand the haricot bean's stage-specific Kc. Using a non-weighing lysimeter and the water balance approach, this study generated knowledge-based data on haricot bean ETc and Kc.

Seasonal haricot bean ETa values in 2017 and 2018 were 493.0 mm and 410.1 mm, respectively, with a mean of 451.6 mm. For the first, middle, and end of the season in 2017, the developed haricot bean Kc values were 0.46-0.5, 1.14-1.15, and 0.66-0.73, respectively. The Kc values for the first, middle, and end of the 2018 season, on the other hand, were 0.41-0.64, 1.15-1.18, and 0.63-0.65, respectively. In the first, middle, and final seasons of the two experimental years, the average seasonal haricot bean Kc values were 0.5, 1.16, and 0.67, respectively. The locally produced Kc values were greater when compared to the FAO-adjusted Kc values over the course of the growing period. It demonstrated that crop water requirements were higher locally than the FAO

reference values. This can be the result of crop traits and local climate circumstances. Overall, this study offers helpful information about the precise water applications and effective irrigation water management in nations that grow haricot beans in semi-arid regions. Based on the above conclusion, the following recommendations are proposed:

1. The locally developed stage-specific crop coefficients (Kc) for haricot bean should be adopted by irrigation planners, extension services, and farmers in semi-arid regions, as they better reflect local climatic conditions and crop responses than FAO-adjusted values.
2. Irrigation scheduling for haricot bean production should be based on experimentally determined ETc and Kc values to improve water-use efficiency, avoid over- or under-irrigation, and minimize yield losses due to water stress.
3. National and regional irrigation guidelines should be updated to incorporate locally calibrated crop coefficients for major crops, including haricot bean, rather than relying solely on generalized FAO reference values.
4. Further studies should be conducted across different agroecological zones, soil types, and management practices to validate and refine haricot bean Kc values, ensuring their wider applicability under diverse semi-arid conditions.
5. Future research should evaluate the performance of the developed Kc values under deficit and supplemental irrigation scenarios to support water-saving strategies in water-scarce environments.
6. Capacity-building programs for irrigation engineers, extension agents, and farmers should emphasize the importance of locally derived ETc and Kc values for precise water management and sustainable irrigated agriculture.
7. Policymakers and water resource managers should use the findings of this study to support evidence-based water allocation decisions, particularly in regions facing increasing competition for limited water resources.

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Groundwater Resources Assessment and Use for Sustainable Agricultural Commercialization: The Case of Integrated Shallow Groundwater Irrigation Development Project

Getachew Zewdie*, Addis Abera Birru, Kassahun Teka, Abdo Kedir, Abenezer Kefeni, Seyoum Getachew, Kebede Teshome, Dawit Setegn, Mucheye Adugna, Alemu Teketel, Birhanu Maru, Hailay Hagos, Mengistu Aragie and Aweke Mulualem

Ethiopian Agricultural Transformation Institute (ATI), P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding author: getachew.zewdie@ati.gov.et

Abstract

Erratic rainfall patterns pose significant challenges to the food security of smallholder farmers in Ethiopia. The unpredictable changes in the timing, intensity, and distribution of rainfall disrupts traditional farming calendars, reduce crop yields, and ultimately jeopardizes the livelihoods smallholder farmers. The Integrated Shallow Groundwater Irrigation Development Project is a pioneering national initiative designed to enhance smallholder farmers' access to shallow groundwater for irrigation. Remote sensing, geological and hydrogeological mapping and groundwater recharge estimation methods were applied to delimitate the potential of shallow groundwater and quantify the rechargeable amount of groundwater in the range of 30m depth across 234,772 km² and identified 27.01 bm3 of groundwater suitable for irrigation and drinking, capable of supporting 3 million hectares of farmland, benefiting 6 million households. To ensure sustainable use, the project promoted 3R approaches (Recharge, Retention, Reuse) and developed 267 groundwater atlases for local planning. In parallel, the project strengthened business groups by establishing 226 MSMEs, training 595 youth (including 54 women) in well drilling, pump maintenance, and manual pump manufacturing, enhancing local irrigation technology supply chains. High-value crop production was promoted using crop prioritization tools, resulting in 153,148 hectares of market-oriented crops cultivation and 10.7 million quintals of produce. To support climate-smart irrigation, 247 farmers were equipped with solar pumps and water saving irrigation systems, with 6,555 farmers trained in the operation and maintenance of these systems to ensure their long-term functionality. This comprehensive approach highlights the project's transformative potential in improving water access, enhancing livelihoods, and promoting climate-resilient smallholder farming.

Keywords: High value crops, Remote sensing, Resilient, Solar pumps, water saving systems

1. Introduction

Ensuring food security for Ethiopia's rapidly growing population, which is exceeding 109 million (ESS, 2024), is a critical challenge that requires innovative interventions. The distribution of natural resources alone cannot meet the increasing demand; instead, a strategic approach that integrates key factors is necessary to overcome

existing bottlenecks. Given the challenges of global climate change, it is essential to assess the feasibility of projects from both local and global sustainability perspectives. This approach ensures ecological balance and the continuous supply of resources to meet our needs.

The Ethiopian Agricultural Transformation Institute (ATI), tasked with addressing systemic bottlenecks in Ethiopia's agriculture sector, works to enhance the capabilities of the Ministry of Agriculture (MOA) and other public, private, and non-governmental partners. ATI has identified household irrigation as a key component of the agricultural system. The purpose of ATI's household irrigation program is to support the Agricultural growth program by promoting small-scale irrigation activities at the household level. This initiative focused on providing implementation support across the value chain, including the identification of water resources and appropriate technologies, in collaboration with the Ministry of Agriculture, Bureau of Agriculture (BOAs) and other implementation partners.

As an entry point to this plan, the ATI aimed first at quantifying shallow groundwater resources in 200,000 km² and to identify 500,000ha potential irrigable command benefit 1 million smallholder farmers of which at least 30% are female. Shallow groundwater (SGW) represents a critical yet underutilized resource that could greatly enhance Ethiopia's agricultural productivity. Unlike surface water and rainwater, which are subject to seasonal variability and regional constraints, SGW is more consistently available across diverse regions of the country. Harnessing SGW for irrigation presents an opportunity to mitigate the adverse effects of erratic rainfall and extend growing seasons for smallholder farmers.

The Integrated Shallow Ground Water Mapping for Irrigation Development (ISGWID) project intends to contribute to improved food security and increased income for all SHFs through increased sustainable production and productivity, irrigation practices and expanding irrigable areas. The project designed to achieve four main outcomes: enhancing access to applied knowledge and information to enable sustainable utilization of SGW resources, improving access to job among youth and enhance access to irrigation technologies to SHFs through Promotion of Business Groups (PBGs), increase irrigation areas, market-driven high value crops (HVCs) production and productivity, and enhance adoption of energy efficient (EE) and water saving technology (WST) among SHFs, which labelled as component I, II, III and IV, respectively.

2. Materials and Methods

2.1. Description of implementation site

Geographically, the study area encompasses Central Ethiopia part of Upper Awash basin (Oromiya, SNNP), Southeastern Ethiopia part of Genale basin (Oromiya, former SNNP), Tana-Beles and Tarmaber-Michew part of Tana-Beles catchment and lower

Awash basin (Amhara, Benishangul Gumuz and Tigray), Fincha-Gimbi; Tepi-Gibe (Oromia, former SNNP), Axium-Adiremets (Tigray), Adigrat-Abergele (Tigray), Chancho-Mehal Meda (Oromiya, Amhara), Kofale-Goba (Oromiya) and Harari regions.

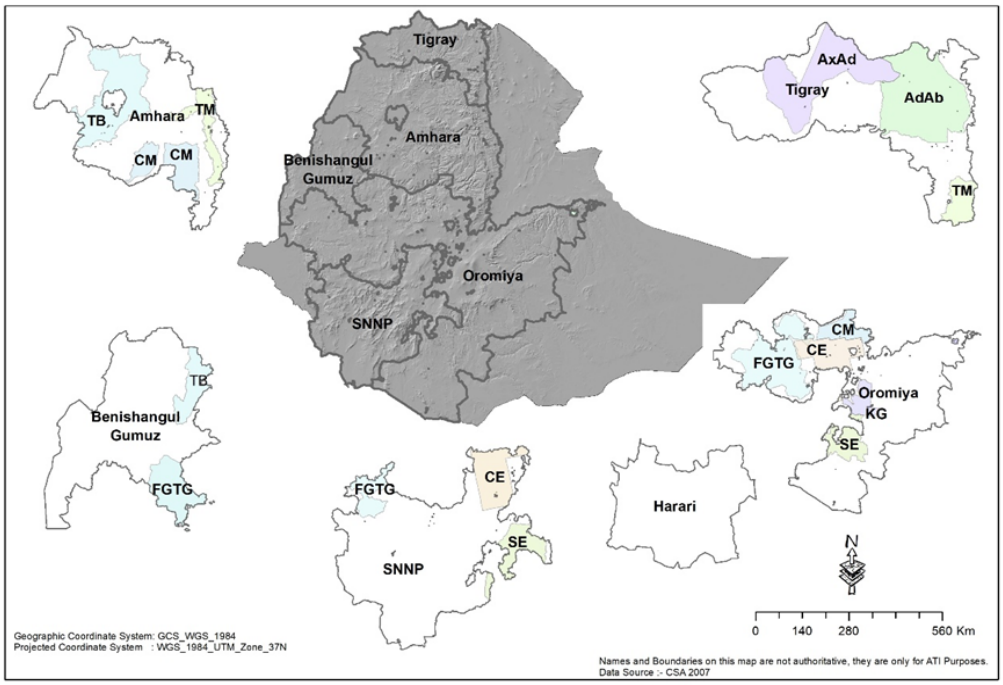

Figure 15**.** Geographic location of the project intervention areas**.** Central Ethiopia (CE), Southeastern Ethiopia (SE), Tana-Beles (TB), Tarmaber-Michew (TM), Fincha-Gimbi; Tepi-Gibe (FGTG), Axium-Adiremets (AxAd), Adigrat-Abergele (AdAb), Chancho-Mehal Meda (CM), Kofale-Goba (KG) and Harari region.

2.2. Operational design/model of the project

Comprehensive, and multi-phased methodologies were developed to study and implement shallow groundwater mapping and sustainable utilization, promotion of business groups and youth entrepreneurship, promotion of high-value crop (HVC) production and market linkages, and energy-efficient water lifting and saving technologies. In shallow groundwater potential study, various types of materials and software were used including ArcGIS, QGIS, Global Mapper, and density mapping technology (DMT).

The Shuttle Radar Topography Mission (SRTM 30 m) data were used to derive the digital elevation model (DEM), (Dikau *et al*., 1989; Kaab *et al*., 2005; Hancock *et al*., 2006). The pre-processed DEM was used for extraction and quantification of morphometric parameters. Geological maps at a scale of 1:250,000, and hydrogeological maps at a scale of 1:250,000 acquired from Geological Survey of Ethiopia used to assess shallow

groundwater potential. For groundwater recharge estimation various methods were deployed including BILAN Base flow separation method (Kašpárek *et al*. 2003), WETSPASS method (De Smedt *et al*., 2001; Batelaan and Woldeamlak, 2004), HBV method, Infiltration Coefficient method (BCEOM, 1998), Base-flow separation (Geo-Engineering Service, 2003; Getachew Zewdie, 2010) and water level fluctuation method. CROPWAT was also used for analysis and interpretation of irrigation water requirements. Vertical Electrical Sounding (VES) survey was conducted over the selected target areas to support hydrogeological investigations (Telford *et al*., 1990). The purpose of the VES survey was to map saturated thickness of the shallow and very shallow aquifers, to identify the depth to bedrock underneath the overburden materials and to identify potential salinity problems. AB/2 of 330 meters with Schlumberger array was used in the survey. Yield characteristics of different shallow and very shallow aquifers were observed in the field based on record of filling rate of hand dug wells once the water is pumped out, as well as based on water level fluctuation between the dry and the wet seasons. 3R techniques were employed to enhance groundwater recharge and soil water holding capacity.

In collaboration with local and internation partners, both theoretical and practical trainings were arranged to provide training on entrepreneurial and business orientation to youth and community members to set up businesses centered around SGW based irrigation (well drilling, pump maintenance and installation, and repair services), practical training in the field on manual well drilling, and semi-automatic drilling. Appropriate platform for HVC selection tools employed to select appropriate high value crop selection with respect to agroecology within the intervention regions. Based on the selected tools, training materials were prepared to provide for woreda experts on crop calander and irrigation water management. Promotion of energy efficient and water saving technologies were undertaken based on water resource availability, agricultural potential, and off-grid energy constraints. The delivery and distribution of solar pumps was conducted by establishing farmer selection criteria to avoid conflict of interest among SHFs.

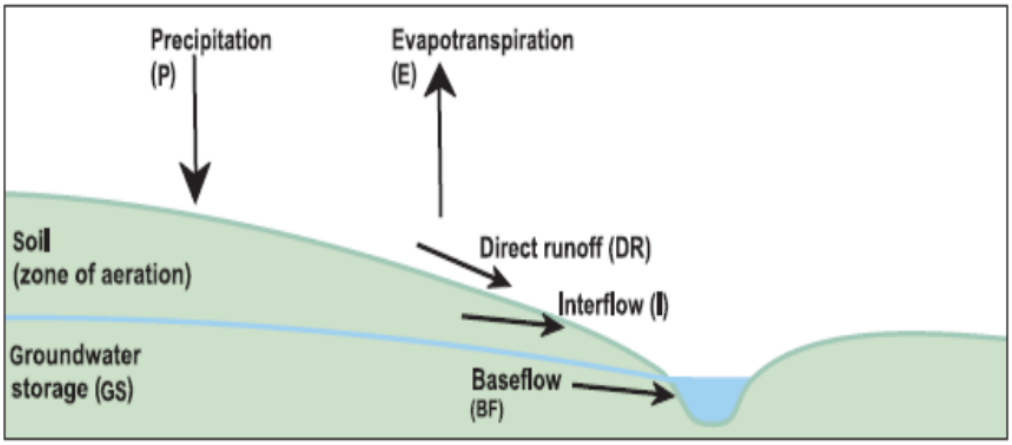

Figure 16*:* Schematic description of hydrological components to estimate groundwater recharge

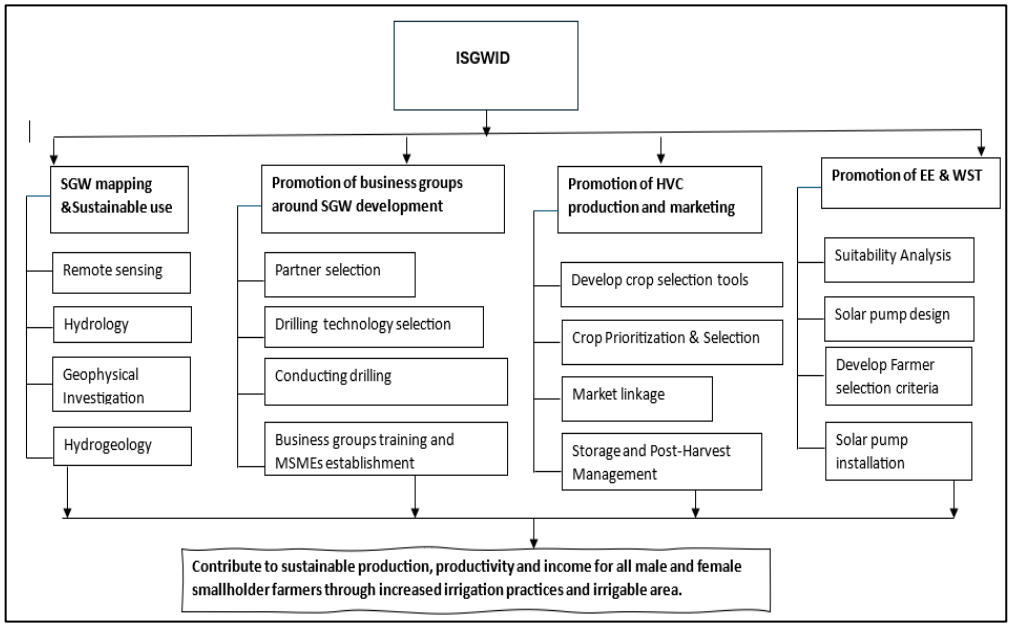

Figure 17: Flowchart of used methodology to accomplish ISGWID

3. Results and Discussion

3.1. Shallow groundwater mapping and sustainable utilization

The project aimed to provide accurate and reliable information on shallow groundwater (SGW) availability to government institutions, smallholder farmers, and private sector stakeholders while building regulatory capacity to prevent water resource depletion (Yilak *et al*., 2015). Hybrid catchment-based recharge was estimated to evaluate renewable shallow groundwater volume and irrigation

command areas identified based on the yield capacity of shallow groundwater aquifers and available groundwater volume, (Dessie Nedaw, 2003). Initially planned to cover 200,000 km², the project exceeded expectations by mapping 234,772 km², identifying a significant 27.01 billion cubic meters of groundwater reserves. This resource has the potential to irrigate over 3 million hectares of farmland and sustainably benefit more than 6 million smallholder households. The findings revealed that SGW is widely distributed across rural smallholder farms, making it an accessible and cost-effective irrigation solution when combined with semi-manual well drilling technology and climate-smart water-lifting techniques.

To disseminate these findings and create awareness, an integrated groundwater resource map was developed, alongside 263 SGW atlases, which were published and distributed to 193 woredas through workshops and training programs. Additionally, digital versions of the mapping data were preloaded onto tablets for field use, ensuring that decision-makers and farmers will have easy access to critical water resource information for productive site selection, efficient irrigation planning and sustainable groundwater management. To ensure the long-term sustainability of SGW development for household irrigation (HHI), two groundwater monitoring wells were installed in Oromia and Sidama regions. This initiative was complemented by the promotion of the 3R approach (Recharge, Retention, Reuse) to regulate groundwater use and prevent depletion by recommending optimal well spacing, and daily pumping limits (Kumar *et al*. 2011). Additionally, targeted technical training on SGW exploration technologies, including navigational tools and geophysical instruments like Tromino was provided to 386 regional, zonal, and woreda experts to strengthen field skills and implementation capacity.

The project also collaborated with the Ministry of Water, Irrigation, and Energy (MOWIE) to procure, install, and establish a national groundwater database. The Hydro-GeoAnalyst software was set up at ATI headquarters and MOWIE servers, enabling the organization, analysis, and visualization of water-related data at a national level. This interactive groundwater database will serve as a vital tool for monitoring groundwater resources and supporting future hydrogeological studies, ultimately aiding policymakers in making informed water resource management decisions. To further enhance SGW assessment, 169 navigational tools were distributed to potential woredas, and 56 water test kits were delivered to the Water Development Offices of Amhara, Oromia, Tigray, and SNNP regions to assess groundwater quality for drinking and sanitation purposes. For the effective implementation of the ISGWID project's findings and recommendations, the team worked with MoWIE to review and integrate shallow groundwater sustainable utilization policies into the existing national water policy. This ensures that SGW resources can be effectively managed and utilized for small-scale irrigation, strengthening Ethiopia's long-term agricultural resilience and

food security, (NMA, 2007).

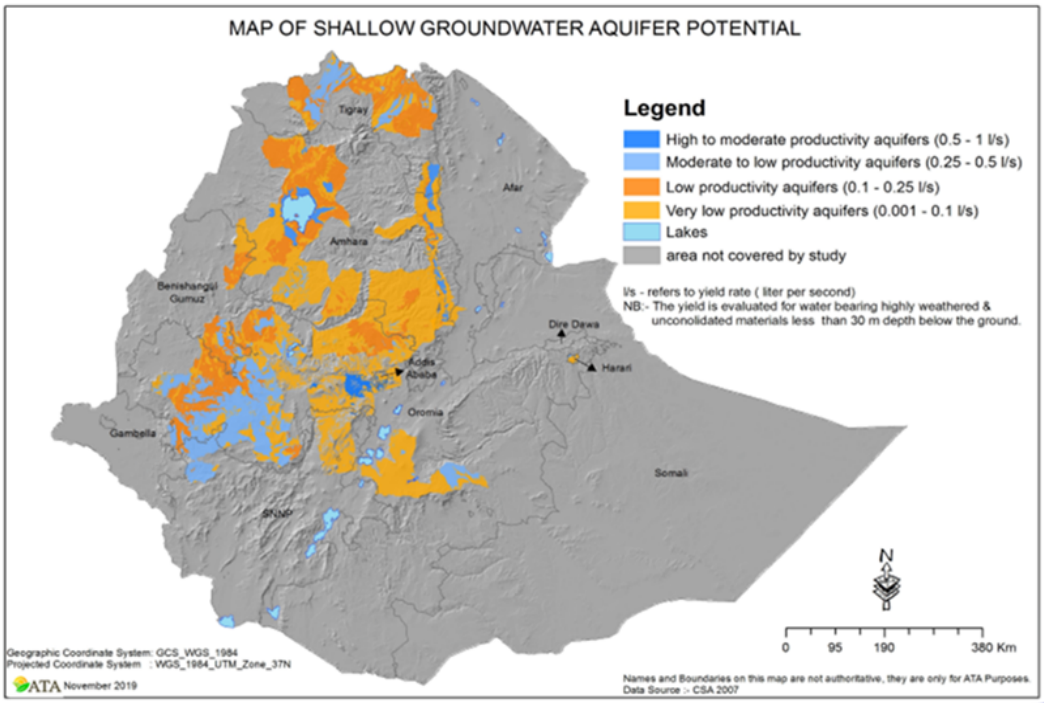

Figure 18: Map of shallow groundwater aquifer potential over 234,772sq. Km area

Table 14. Summary result of shallow groundwater mapping Summary result of shallow groundwater mapping

Region	Area Coverage(km2)	Annual Renewable GW Recharge (Mm3)	Irrigation Capacity (ha)	Potential HH number to be served(0.5ha/HH)
Oromia	110,820.72	15,491.20	866,990	1,865,682
Former SNNP	24,593.79	1,671.19	60,019	167,386
Tigray	21,601.92	1,115.34	45,913.3	91,802
Harari	331.93	12.82	497.9	995
Benishangul-Gumuz	8,730.45	1,198.20	36,375.6	72,765
Afar	698.55	10.00	631.1	1,262
Amhara (Groundwater & surface water conjugate use)	67,994.65	7,508.05	2,077,967.78	3,977,006
Total	**234771.9964**	**27,006.81**	**3,088,395.00**	**6,176,898**

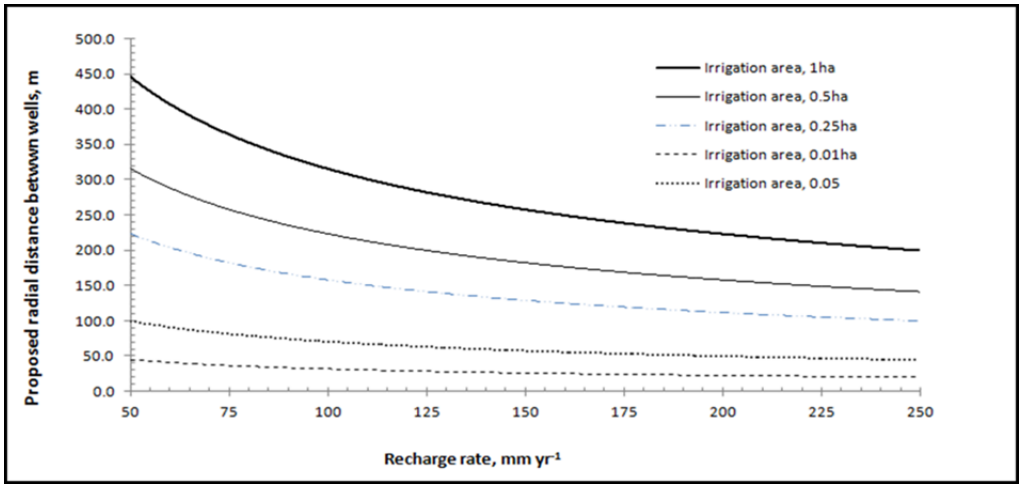

Figure 19: Proposed well spacing corresponding to recharge zones and acreage of land each scheme is intended to irrigate.

Figure 20: Installed groundwater monitoring device to regulate water level fluctuation and measure salinity of groundwater

Figure 21. Community engagement participating in 3R (recharge retention and reuse) structures for enhancement of groundwater recharge

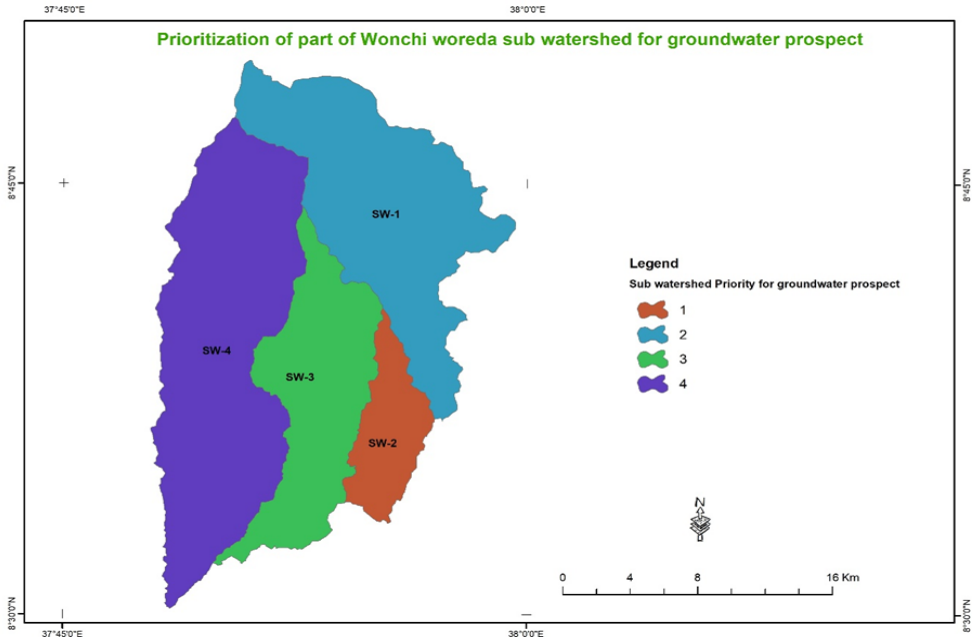

Figure 22: Map shows prioritized sub-watershed with their ranks for 3R implementation in Wonch woreda

3.2. Promotion of business groups around SGW development

The second key component of the project was focused on organizing youth entrepreneurs and promoting business groups in areas with high shallow groundwater (SGW) potential. The primary objectives were to strengthen the irrigation technology supply chain, increase the adoption of water-lifting technologies, and expand the availability of well-drilling services to smallholder farmers (SHFs). Through this initiative, 77 Micro, Small, and Medium-Sized Enterprises (MSMEs) were established, consisting of 296 members, including 18 women. These enterprises received training in well-drilling techniques, enabling them to provide 2,500 well-drilling services for small-holder farmers. In addition to well drilling, the project targeted the maintenance and servicing of irrigation pumps, which are essential for ensuring the continuous operation of irrigation systems.

To address this need, 90 MSMEs were formed, comprising 183 members, including 21 women. These enterprises were trained in surface engines and submersible pump maintenance, and they have since delivered 4,067 maintenance services to smallholder farmers, ensuring minimal downtime for irrigation systems and improving overall irrigation efficiency. Further supporting irrigation technology development, the project promoted local pump manufacturing by organizing 59 MSMEs with 116 members, including 15 women. These enterprises were trained in manual pump production and subsequently manufactured 1,779 manual pumps, which are owned by smallholder farmers along with maintenance support services. This intervention enhanced access

to affordable and locally produced irrigation technologies, reducing reliance on imported equipment and strengthening domestic irrigation technology supply chains.

Figure 23: Manual well drilling trained group, Hosanna.

3.3. Promotion of high value crops production and marketing

The project prioritized market-driven HVC production by developing a woreda-specific crop calendar and a software package for crop prioritization, enabling year-round income generation for smallholder farmers. A total of 1,179 woreda experts, subject matter specialists (SMSs), and development agents (DAs) were trained in HVC selection, localized cropping calendars, irrigation water management, and agronomy, leading to the successful cultivation of 153,148 hectares of land and the production of 10,709,959 quintals of marketable crops.

To address post-harvest losses, the project introduced Zero Energy Cool Chambers (ZECC), an eco-friendly and cost-effective storage solution requiring no external energy. Five ZECC units were constructed in Amhara, Oromia, and former SNNP regions, helping farmers reduce spoilage, extend shelf life, and sell crops at optimal market prices. By integrating HVC prioritization tools, improved irrigation practices, and innovative storage technologies, the project strengthened market engagement and enhanced smallholder farmers' productivity and profitability, contributing to a more resilient and sustainable agricultural sector.

Figure 24: Zero Energy Cool Chamber (ZECC) Demonstration

3.4. Promotion of energy efficient (EE) and water saving technologies (WST)

The promotion and demonstration of energy-efficient water lifting and saving technologies, particularly solar pumps and drip irrigation systems, represent a key outcome of the ISGWID project. These technologies provide a sustainable and cost-effective solution for smallholder farmers by enabling groundwater extraction for irrigation, household use, and other productive activities (Metaferia Consulting Engineers, 2017). By reducing dependency on conventional fuel-based pumps, the adoption of solar-powered irrigation enhances energy efficiency, lowers operational costs, and minimizes environmental impact. To showcase the benefits and practicality of these technologies, solar pumps and drip irrigation systems were installed and demonstrated at 247 model farmers' fields and Farmers' Training Centers (FTCs) across four regions Oromia, Amhara, former SNNPR, and Tigray. These demonstration sites played a critical role in illustrating how energy-efficient irrigation can improve agricultural productivity, enhance water-use efficiency, and ensure year-round high-value crop production. The successful implementation of these technologies has provided smallholder farmers with a practical alternative to traditional irrigation methods, reducing water wastage while increasing farm output.

To ensure long-term sustainability and widespread adoption, extensive training and awareness sessions were conducted, reaching 6,555 farmers. These efforts focused on the operation and maintenance of solar pumps, the proper use of drip irrigation systems, and the economic benefits of adopting such technologies. As a result, many farmers are expected to independently purchase and install these systems from local suppliers in the future, indicating a growing demand for energy-efficient irrigation solutions. This shift will further strengthen smallholder farmers' resilience to climate

variability and enhance their capacity to produce high-value crops for market-oriented farming.

Figure 25: Solar pumped drip irrigation system

4. Conclusion and Recommendations

Integrated shallow ground water for irrigation development project is the most comprehensive, feasible and climate smart project which addresses the smallholder farmer's food security problem by availing technology and water for high value crops production. It can increase farmers income by two to three folds through the adoption of climate smart water lifting technology, production of high value crops and creation of jobs for youth and women in the rural areas. The project successfully mapped shallow groundwater resources across a vast area, providing critical data that can support sustainable irrigation practices and improve food security for over 6 million smallholder households. By integrating modern technologies and focusing on capacity-building initiatives, the project has established a solid foundation for better groundwater resource management in Ethiopia. The collaboration with MOWIE, alongside the development of a national groundwater database, will play a key role in the future management of SGW resources.

The project has successfully created sustainable business opportunities for youth entrepreneurs and MSMEs, while addressing critical gaps in irrigation technology services and maintenance. By focusing on locally sourced solutions, such as well-drilling and pump manufacturing, the project contributed to improving smallholder farmers' access to affordable irrigation technologies. It also demonstrated the potential for

entrepreneurial ventures to foster economic growth, employment, and gender equality within the agricultural sector.

The integration of HVC prioritization tools, localized cropping calendars, and post-harvest loss reduction technologies significantly improved smallholder farmers' productivity and market engagement. Strengthening market-driven production systems through capacity building, efficient irrigation management, and innovative storage solutions is crucial for ensuring sustainable agricultural transformation and rural economic resilience. Further scaling of ZECC technology and wider adoption of digital crop planning tools will enhance long-term sustainability and profitability in the sector.

The promotion of energy-efficient water lifting and saving technologies has demonstrated promising results in increasing smallholder farmers' access to sustainable irrigation solutions. The widespread adoption of solar pumps and drip irrigation systems has the potential to enhance agricultural productivity, improve water-use efficiency, and build resilience against climate variability. The ISGWID project has successfully introduced and validated these technologies, proving their viability for smallholder irrigation in Ethiopia. However, scaling up these solutions requires overcoming key financial, technical, and institutional barriers.

The introduction of reliable and cost-effective mapping technologies, developed in consultation with stakeholders, has significantly improved the accessibility and usability of groundwater data for irrigation purposes. By employing advanced mapping techniques, decision-makers and communities gained better insights into resource availability, enabling more informed planning and management. Defining sustainable groundwater use, alongside proper management strategies such as recharge enhancement and well-spacing regulations, ensured controlled abstraction rates to maintain long-term resource health. Additionally, tailored technical training on shallow groundwater exploration technologies including the use of navigational tools and geophysical instruments (Tromino) has strengthened the field skills and implementation capacity of regional, zonal, and woreda experts, ensuring sustainability by embedding expertise within the existing government structure. Validation workshops and field verification exercises conducted through ground-truthing with stakeholders fostered ownership and commitment at both regional and local levels. The adoption of energy-efficient, water-saving technologies and tools for HVC selection, along with the practice of cropping calendars, has improved agricultural production and productivity in the face of climate change.

Furthermore, establishing and strengthening MSMEs around irrigation service provision including well drilling, pump maintenance, and manual pump manufacturing has significantly improved farmers’ access to essential technologies. The introduction of zero energy cool chambers (ZECC) also demonstrated the potential for cost-effective, energy-free storage solutions, extending crop shelf life and enhancing quality, which if

scaled up, could further reduce post-harvest losses and boost farmer incomes. Based on this, the recommendations below need further action.

- Strengthening platform in each level for coordination among different stakeholders and enhanced access to result
- Expand SGW mapping to other potential areas and integrate findings into regional and national irrigation planning.
- Strengthen policy frameworks to regulate groundwater use and prevent over-extraction.
- Increase financial and technical support for local enterprises involved in irrigation technology supply chains.
- Enhance farmer awareness and training on climate-smart irrigation and sustainable water management.
- Foster stronger collaboration among government agencies, private sector players, and development partners to scale up SGW irrigation development
- Expanding remote sensing and GIS based water harvesting or 3R implementation for soil water conservation techniques is very useful to recommend environmental suitability and optimum conservation structures.
- Long-term monitoring wells were key strategies in addressing concerns about groundwater depletion and ensuring that SGW resources could be used sustainably by smallholder farmers.
- Efforts should be made to enhance market linkages for locally produced irrigation equipment, including advocating for government incentives to promote local manufacturing and reduce barriers to market entry for domestic products.
- Encouraging private-sector involvement in the development of SGW resources, especially in terms of innovative technologies for water lifting, will help ensure that these resources are efficiently utilized at scale and remain sustainable over the long term
- Promoting water-saving irrigation technologies such as solar pumps and drip irrigation systems helped optimize water use efficiency and reduce dependency on erratic rainfall.
- Scaling up ISGWIDP successes, ensuring sustainability, and enhancing impact through policy integration, capacity building and technology adoption.

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Enhancing Soil Health and Climate Resilience: The Soil Health and Fertility Management Project's Approach to Sustainable Agriculture

Girma Abera* and Aweke Mulualem

Ethiopian Agricultural Transformation Institute (ATI), P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding Author: girma.abera@ati.gov.et

Abstract

Ethiopia's agricultural soils have been facing significant health and fertility challenges, including soil erosion, nutrient depletion, loss of organic matter, soil acidity, and salinity. These challenges are further exacerbated by climate change. The Soil Health and Fertility Management Project aimed at addressing these issues by promoting sustainable soil health and fertility management practices for enhancing productivity of Farmers' Production Clusters. Key efforts included strengthening soil information systems, building capacity of farmers, development agents and experts, and helping both government and non-government actors in managing soil fertility and health. The project also focused on improving natural resource management and building climate resilience. Despite implementing climate-smart agriculture practices, such as crop rotation and integrated soil fertility management, these practices were not systematically tracked until 2023. To remedy this, the SHFM project developed data recording templates and conducted capacity building trainings on soil health, climate-smart agriculture and vermicompost production and marketing business models. Achievements include improved capacity of farmers, development agents and experts across Agricultural Commercialization Cluster regions; six vermicompost centers established (two each in Amhara, Oromia and former SNNP regions). Consequently, integrated soil fertility management (ISFM) practices were adopted by over 2.2 million farmers (1,908,768 males and 310,730 females), which resulted in improved health and fertility of soils, and enhanced climate resilience of farmers.

Keywords: Capacity building, FPC, Demonstration, soil health and fertility, vermicompost

1. Introduction

Healthy and fertile soils are central to Ethiopia's agricultural production, directly impacting crop and livestock productivity, and environmental sustainability. Fertile soils play a key role in economic growth, biodiversity conservation, agricultural sustainability, and food security. However, according to Kibebew *et al*. (2022), significant challenges persist, including rising soil acidity, nutrient depletion, loss of organic matter, seasonal waterlogging of Vertisols, salinity, and widespread soil erosion. To effectively address these issues, a holistic approach that integrates prevention, remediation, and mitigation is needed.

While the Government of Ethiopia (GoE) has long aimed to boost agricultural production and productivity, its focus on short-term productivity gains over the past three decades has limited the success of soil health and fertility management efforts. Additionally, soil extension in Ethiopia has not been driven by demand, nor has it been based on the needs of farmers or their involvement in the process. Soil extension has primarily been driven by the government, with limited participation of the private sector. These issues call for a more balanced, inclusive and long-term strategy to achieve sustainable improvements in soil health and agricultural productivity.

Application of organic fertilizers have multiplicative effects by addressing multiple issues simultaneously, highlighting the importance of a comprehensive strategy. For example, adding organic fertilizers such as compost or vermicompost not only replenishes essential nutrients (e.g., nitrogen, phosphorus, and potassium) but also improves soil structure. Further, it enhances water infiltration, aeration, and reduces soil compaction, thus mitigating surface runoff. Furthermore, organic matter binds soil particles together, reducing erosion and protecting the soil from both wind and water erosion. Additionally, organic amendments play vital roles in carbon sequestration, helping to mitigate climate change by storing carbon in the soil (Paustian *et al*., 2016; Lal, 2004). Given these opportunities, the SHFM project has been promoting production of compost and vermicompost products across FPC woredas under the ACCs Program, mainly working with model farmers through building their capacities.

In general, the SHFM project has been promoting Integrated Soil Fertility Management (ISFM), which is a comprehensive approach that combines appropriate use of chemical fertilizers, organic resources, improved crop varieties (germplasm), and location-specific adaptive knowledge to optimize soil fertility and ensure sustainable agricultural production. This approach involved targeted use of chemical fertilizers to replenish essential nutrients, incorporation of organic materials such as compost and vermicompost to improve soil health, and the use of locally adapted crop varieties to enhance resilience to local conditions (Bationo and Waswa, 2011). Key practices were including managing acidic soils with agricultural lime (ag lime) to adjust pH levels and using the Aybar Broad Bed Maker (BBM) to manage Vertisols, improving drainage and soil aeration for better root growth and crop productivity.

The SHFM project was implemented across Six key regions (Amhara, Oromia, South Ethiopia, Southwest Ethiopia, Sidama and Central Ethiopia) focusing on enhancing soil management practices. Beyond soil health, the project has been actively promoting climate-smart agriculture (CSA) practices within the farmers' production clusters (FPCs) and agricultural commercialization cluster (ACC) woredas in the intervention regions. Through those efforts, the SHFM project aimed to achieve sustainable, productive, and climate-resilient agricultural landscape in Ethiopia. The overarching goal of the project was to advance climate-smart, soil health and fertility management practices across Ethiopia's agricultural landscapes by facilitating support, coordination, and collaboration with both national and international agencies and experts.

2. Materials and Methods

2.1. Description of implementation sites

The Soil Health and Fertility Management (SHFM) project has been implemented on FPC farmers plot within the ACCs across six regions: Amhara, Oromia, South Ethiopia, Southwest Ethiopia, Sidama and Central Ethiopia. The FPC project is a subset of the ACC program that has been launched in November 2019 (Techane *et al*., 2022). FPCs offer a more comprehensive approach across the crop value chain, primarily focusing on farmer-level interventions by clustering farmers to increase the scale of agronomic practices. The programme aims to promote full application of agronomic recommendations, enhance the use of mechanization services, reduce post-harvest losses, encourage inclusiveness, and maintain environmental sustainability (ATA, 2019).

2.2. Operational design/model of the project

The SHFM project followed a clustering approach designed to facilitate farmers' access to various soil health management technologies that enable surplus production in FPCs woredas, thereby enhancing their economic and social wellbeing.

The project was designed as a complementary project for FPCs to sustainably manage soil, water and land resources, and to mitigate climate change risks. Clustering is an approach of grouping farmers owning adjacent farm plots with the aim of consolidating their farm activities and providing targeted support across key segments in the value chain, particularly, input and service supply, on-farm production, post-harvest handling and marketing. Accordingly, farmers were selected and clustered with different selection criteria for FPC cluster formation. A similar approach was followed for implementation of the SHFM project in the four ACC regions (ATA, 2019). Each farmer voluntarily joins a cluster with a minimum of 0.25-hectare farm share per farmer to have at least 15 hectares of neighbouring lands in the cluster.

2.2.1. Beneficiary selection

The beneficiaries were selected on a voluntary basis. Host farmers in the FPC woredas who met the criteria set by the project were also voluntarily involved in implementing SHFM project interventions. The selection criteria included land ownership and willingness to implement sustainable soil management practices.

2.2.2. Data collections and analysis

Data from the SHFM project were recorded using standard procedures at the woreda level, then aggregated by zones and further compiled by respective regional Bureau of Agriculture (BoA) and ATI centres. This data captured both outputs (improved soil (health) management and improved water management) effectively. Most of the data generated were analysed using descriptive statistics. Model farmers were selected voluntarily from the ACCs/FPCs woredas for capacity building training and to host demonstration plots.

3. Results and Discussion

The soil health and fertility management (SHFM) project operated under the ACCs outcome 3, which aims to enhance environmentally sustainable farm practices. The project introduced various innovations and technologies to smallholder farmers affiliated with FPCs woredas across different regions of Ethiopia. Additionally, numerous capacity development trainings were provided, and dialogue forums were facilitated at both regional and federal levels, often in partnership with regional Agricultural Transformation Centres and the MoA (Figure 1). Through these efforts, the SHFM project endeavored to enhance resilience and sustainability of Ethiopia's agricultural sector.

Climate Smart Agriculture (CSA) practices are pivotal for promoting sustainable agriculture and creating healthy environments within Ethiopia's FPCs agricultural landscapes. The Ethiopian Agricultural Transformation Institute (ATI) has focused on these priorities as outlined in the ACC PAD, with significant capacity-building achievements over the fiscal years 2023 and 2024. Key initiatives included training model farmers in vermicomposting and vermi-worm culture production, enhancing technical expertise in soil health and CSA for local stakeholders, soil input support such as providing Aybar Broad-Bed Maker (BBM) implements for Vertisols management, and supply of ag lime for soil acidity management. Further, a national climate-smart agriculture mainstreaming platform was established. These actions collectively advanced soil health management and supported sustainable agricultural development in project areas.

3.1. Model Farmers Capacity Building Trainings

Vermicompost and vermiculture production, management, and business plan training sessions to model farmers were conducted in three regions (29 model farmers in Amhara, 23 model farmers in Oromia, and 30 model farmers in former SNNP/Sidama regions) of Ethiopia, during January 12-14/2023, February 24-26/2023 and February 28 to March 2/2023 in Bahir Dar, Jimma and Hawassa, respectively (Table 1). Model farmers were selected from the ACC/FPC woredas, and the trainings were designed to be highly interactive and participatory. The trainings consisted of both theoretical and practical components, delivered in an interactive and participatory manner. The theoretical trainings took place in a training hall, where key concepts and techniques were discussed. The practical trainings, on the other hand, involved hands-on demonstrations of all the steps required for vermicompost production, including the necessary inputs and materials. This combination of classroom learning, and field demonstrations ensured that participants not only gained theoretical knowledge but also acquired the practical skills needed to implement vermiculture techniques effectively. Participants were given the opportunity to ask questions, confirm their understandings and discuss the relevance of each aspect of the trainings to their local contexts. Accordingly, the participants made a business plan individually as well as in group.

Model farmers were equipped with skills /methods of rearing vermi-worms and identifying characteristics of good quality vermicompost. The farmers who participated in the trainings expressed strong enthusiasm and commitment to applying what they had learned. For example, a farmer from Arba Minch showed a keen interest in vermicomposting technology and committed to allocating 100,000 birr to produce vermicompost for use on his commercial banana farm, demonstrating the practical application and potential of the training in improving agricultural productivity and fostering sustainable farming initiatives.

The main reasons why farmers trained on production of vermicompost (organic fertilizer) and its utilization is that their farmland soils are depleted of organic matter; the price of inorganic fertilizers has become unaffordable by smallholder farmers. At the same time, the agronomic efficiency of fertilizers becomes very low, even if the synthetic fertilizers are available at cheaper prices. Further, soil organisms are vital components of the soil system to offer healthy and fertility conditions to the soil. However, in organic matter depleted soils, soil organisms are absent as they don't have organic carbon that they feed on to get energy and build their cells.

Through the capacity building training, participants gained knowledge and know-how on concepts and principles of SHFM, vermicompost and vermiculture, methods of rearing vermi-worms, methods of vermicompost production and measuring its nutrient contents, identifying the difference between compost and vermicompost and the environmental, economic and social impacts of vermicompost and vermiculture production and utilization.

Table 1. Lists of model farmers and experts participated on vermicompost production (in 2023)

Participants lists	**Number of participants**					
	Amhara		Oromia		South Ethiopia and Sidama	
	Male	Female	Male	Female	Male	Female
Model farmers	29	-	17	3	30	-
Experts	4	-	9	-	2	-
Total	**33**	**-**	**26**	**3**	**32**	-

3.2. Experts' Capacity Development on Soil Health and CSA

Soil degradation and the impacts of climate change pose significant threats to agricultural productivity and the sustainable development of Ethiopia's economy. Addressing these challenges and enhancing the ecosystem and community resilience requires substantial investment in soil health inputs and capacity building at all levels. The capacity development training sessions conducted across four regions of Ethiopia, have proven highly beneficial for both experts and farmers. For instance, in 2023, technical capacity-development training on Soil Health and Climate-Smart Agriculture

(CSA) was provided to 449 stakeholders across ACC's zones and woredas in Oromia, former South Ethiopia and Sidama, and the Southwest Peoples Ethiopia region (Table 2).

In 2024, technical capacity-building trainings on Soil Health and Climate Smart Agriculture (CSA) were provided to 130 experts at the zonal and regional levels in Oromia and Tigray regions (Figure 1). Participants reflected that they gained deeper understandings on soil health and fertility depletion, as well as the challenges posed by climate change. As a result, they are committed to applying the skills and knowledge they acquired during the trainings. The trainings significantly enhanced the participants' ability to optimize agronomic efficiency of fertilizer use and improve soil organic matter management through promoting integrated soil fertility management (ISFM). It also emphasized the importance of resilience and adaptation to climate change using various organic fertilizers, CSA practices, and integrated soil fertility management. Participants left the trainings motivated and encouraged to implement and promote those practices on their farms.

In general, the capacity building training sessions addressed concepts and principles of soil health, concepts of climate change and global warming, evidence and trends of climate change in Ethiopia, climate smart practices for crop production, home gardens and traditional agroforestry systems.

Table 2. Technical capacity building training on soil health and CSA practices.

Participants	ACC Regions				Total
	Oromia	South Ethiopia	Sidama	SWE People	
Regional experts	9	7	7	7	30
Zonal experts	104	73	-	35	212
Woreda experts	126	50	28	12	216
Total	**230**	**130**	**35**	**54**	**449**

At the same time, Additionally, a soil health and CSA data collection template was introduced to participants, enabling them to pass on the knowledge and skills gained to development agents at the grassroots level for effective data collection. Training materials, along with the soil health and CSA data collection template, were provided to participants in soft copy for easy access and further dissemination.

Figure 1: Participants during training session (2023).

3.3. Soil Input Supply and Demonstration

In the highlands of Ethiopia only, over 10 million hectares of arable land is covered by Vertisols (Ali *et al*., 2024), which are prone to seasonal waterlogging, poor aeration, and drainage issues. Tillage is challenging, particularly during the high rainfall period, which can delay planting and reduce productivity. The negative impact due to seasonal waterlogging of Vertisols results in an estimated loss of up to 1.5 billion USD annually. Since Vertisols primarily affect cereal production, effective management is crucial. However, when properly managed, Vertisols can be highly productive. Specialized equipment, such as the Broad Bed Furrow Maker (BBM), is required to manage excess water and prepare seedbeds. The BBM, originally developed and tested decades ago, was later modified into a lighter and more efficient version, the Aybar BBM, by Aybar Engineering Company. This improved version has significantly enhanced Vertisols

management, increasing wheat yields from 0.5 tons per hectare to 3.8 tons per hectare (https://securingwaterforfood.org/innovators/bbm-aybar-engineering).

The SHFM project actively promoted the use of the improved BBM (Aybar BBM) for Vertisols management through procurement and distribution efforts for Amhara and Oromia regions. In 2023, 1,605 Aybar BBMs were procured and distributed, and in 2024, the number increased to 3,714 units. These tools were primarily used to drain excess water from Vertisols (waterlogged) fields, improving soil health conditions and enhance climate adaption capacity of smallholder farmers. The Aybar BBM was particularly effective in treating wheat fields across several zones in Oromia, including Arsi, West Arsi, East Shewa, North Shewa, Southwest Shewa, and West Shewa as well as in various woredas of south Wollo in Amhara region.

Soil acidity is another significant and growing challenge in Ethiopia, with its impact expanding in both geographic coverage and severity. Over the past two years (2023 and 2024), the SHFM project has promoted the use of Ag Lime in the Amhara, Oromia, and former SNNP regions. Demonstration results from the former South Ethiopia region clearly showed notable improvements in crop growth and yields compared to untreated fields. In 2023, the Amhara Agricultural Transformation Center, in collaboration with its partners, conducted ag-lime demonstrations in the Amhara region. Building on the lessons learned from these demonstrations, large areas of land have since been treated with ag lime in the Amhara region. Overall, soil health restoration through ag lime use not only boosts agricultural productivity but also strengthens farmers' resilience to climate-related shocks. Additionally, ATI has supported EIAR and regional research institutions (RRIs) to address the critical challenges of soil acidity, crop varietal options that adapt and tolerate disease and pests (Figure 2).

Figure 2. Integrated soil fertility management (ISFM) demonstration on farmers field (Holeta area, West Shewa zone)

3.4. Key achievements through continuous capacity building, linkage, coordination and support

During the 2024 /2016 E.C. implementation fiscal year the project has achieved:

Improved soil health and/fertility management practices and CSA integrated into FPC grain program implementation:

About 2,219,498 farmers (117% against target) have adopted integrated soil fertility management practices, that would improve soil health, fertility, and climate resilience in FPCs woredas. At the same time, 190,859 farmers have adopted Vertisols management (using Aybar BBM and handmade BBF) on 93,550 hectares of wheat and Malt barley growing cluster farmlands in Amhara region. Besides, in Amhara region, 161,399 hectares of land with 326,088 FPC farmers (25,691 Females) have used compost for soil fertility management and thus, averagely 54 quintals of compost have been used per household level in the region.

Support input procurement and supply to enhance soil health and fertility:

In the same year, 3714 BBM (broad bed furrow maker) was procured for drainage of excess water from Vertisols (waterlogging soils) to improve soil health in Oromia and

Amhara regions. About 3,500 quintals of ag lime were procured and distributed for demonstration in four woredas (850 quintals each) in Amhara region.

Establishment of vermi-worm/compost production business centres

Six vermicompost production centres were constructed in Amhara, Oromia and former SNNP regions (2 centres per each region) (Figure 3). A vermicompost and vermiculture production and business plan training was also conducted in Amhara region. In the South Ethiopia two youth groups were established and concomitantly a training was provided to them (56 female and 4 male) on technical and business development. Similarly, two youth groups were organized in Oromia region in Adisalem vermi- centre (12 females) and at Sabure vermi- centre (14 females). In Jimma Zone of Oromia, some farmers begun commercial vermicompost production and generated revenue amounting 20,000-30,000 Birr from their sales. Similarly, model farmers in the Amhara region sold both vermi-worms and vermiculture for 12,000-30,000 Birr. These efforts represent significant achievements that should be scaled up to benefit other farmers and promote organic fertilizer production and use.

Figure 3. Vermicompost. centres constructed in the regions

Technical capacity building for experts on Soil Health and CSA:
Technical capacity buildings were provided for 70 agricultural experts in Oromia ACC's Zones and Woredas and for 60 agricultural experts Tigray region.

Large scale demonstrations of aglime for acid soils management across regions:
In the former SNNP region, 61 hectares of farm plots were amended using 908 quintals of ag lime. Similarly, in Amhara region, 1,019 hectares of FPC farmland was treated with ag lime by distributing 17,582 quintals of ag lime and for 4,579 farmers (226 Females).

Crop rotation for soil health management and income and food diversification:
Soyabean demonstration was undertaken on 250 hectares of land, where 1,019 male and 64 female farmers participated during the organized field days in South Ethiopia

region and demonstrated on over 35 hectares of land in Buno Bedele Zone of Oromia region as well.

4. Conclusion and Recommendations

Soil is a vital natural resource, providing water, nutrients, and mechanical support for plant growth. However, it is facing significant threats from continuous cultivation, removal of crop residues, and application of insufficient fertilizer inputs, compounded by the impacts of climate change. To address these challenges, the SHFM project, a component of the ACCs Program, was developed. The project successfully enhanced the capacity of smallholder farmers, development agents, and experts by equipping them with the knowledge and tools necessary to address critical issues of soil health and fertility depletion, while also mitigating the risks of climate change to promote sustainable agricultural development. In 2023 and 2024, soil input support was provided through the procurement and distribution of ag lime for soil acidity and Aybar BBMs for Vertisols management. By the end of 2024, approximately 2,219,498 smallholder farmers in FPC woredas (117% of the annual target) adopted integrated soil fertility management practices. These practices included crop rotation, acid and Vertisols management, soil conservation, compost and vermicompost production, utilization of improved crop varieties, and climate-smart agriculture techniques, all aimed at improving soil health, fertility, and climate resilience.

The interventions and technologies introduced by the SHFM project should be continued in a more coordinated and robust manner to further advance sustainable development. The achievements realized by SHFM were accomplished with limited human resources. Given this, we recommend reconsidering the recruitment of additional human resources for future projects, particularly in the areas of soil health and climate change, to ensure more successful implementation and greater impact.

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Gender Role and Pastoralist Women's Involvement in Income Generating Activities: The Case of Gabra Women Involved in Camel Milk Marketing in Gomole and Moyale Districts, Oromia Region, Southern Ethiopia

Dejene Alemayehu*, Yetebarek Hizekeal and Serawit Kumana

Institute of Indigenous Studies, Dilla University, Dilla, Ethiopia
*Corresponding author: dejenea987@gmail.com

Abstract

This study examines the roles and contributions of Gabra pastoralist women in income-generating activities, with particular emphasis on their involvement in the marketing of camel milk in the Gomole and Moyale districts of the Borana Zone, southern Ethiopia. Acknowledging the distinctive socio-economic context of the Gabra community, the research elucidates the intersections of gender, culture, and economic development within pastoralist societies. The study draws on qualitative data collected through key informant interviews, focus group discussions, and direct observation, which were analyzed using thematic analysis. The findings indicate that camel milk marketing constitutes a critical source of income for Gabra women, contributing to enhanced economic autonomy and improved social status within the community. Despite challenges related to inadequate infrastructure, limited resources, and lack of formal training, Gabra women demonstrate considerable resilience and innovation in their entrepreneurial activities. The study underscores the importance of supporting women's roles in pastoralist economies as a means of improving household livelihoods and advancing gender equity. Policy implications emphasize the need for targeted interventions to enhance market access, build capacity, and further empower pastoralist women in income-generating endeavors. Overall, this research contributes to a deeper understanding of gender dynamics in pastoralist communities and highlights the pivotal role of women in promoting sustainable economic development.

Keywords: Livelihood diversification**,** Market access, Pastoralists Women, Women's empowerment

1. Introduction

Women constitute more than half of the world's population (Belay & Lishan, 1997; Gashaw, 2015), and many of whom, particularly in developing nations, experience extreme poverty (Kamunyu & Theuri, 2017). According to the International Labour Organization (ILO) (2020), understanding how current livelihood and economic empowerment initiatives reinforce existing gender roles and responsibilities is a crucial first step toward improving women's economic position and welfare. Emergency measures and related humanitarian aid initiatives are unlikely to address the complex and structural challenges faced by women (Stenglich & Bekele, 2009). Rather,

livelihood diversification, which helps farmers and pastoralists reduce their reliance on livestock as the sole source of household capital, is an essential strategy for achieving this goal (Pantuliano & Wekesa, 2008). Interest in women-owned and operated enterprises has increased because of feminist scholarship and international campaigns promoting women's empowerment (Kamunyu & Theuri, 2017).

Pastoralists' livelihoods are closely tied to their environment, which is frequently affected by shocks such as droughts and floods (Aregu *et al.,* 2011). These recurrent droughts negatively affect income from livestock rearing and significantly hinder animal productivity (Haile, 2008). As a result of prolonged drought and its associated challenges, pastoralist women are increasingly becoming primary income earners within their households (Fontana & Paciello, 2010). Despite traditional gender roles, household structures and divisions of responsibility are being rapidly transformed by major economic and social changes occurring in an increasingly globalized world (Onyebu, 2016).

In the Gomole and Moyale districts of the Borana Zone in southern Ethiopia, Gabra women are actively engaged in income-generating activities, particularly the marketing of camel milk, to support their families during periods of environmental stress and enhance household financial stability. Therefore, research focused on women pastoralists is necessary to understand their perspectives on shifting gender roles resulting from participation in income-generating activities, as well as to identify strategies for managing these changes in ways that promote sustainable and inclusive development. Previous studies on gender roles and pastoralist women's involvement in income-generating activities in the Borana Zone (Ridgewell & Flintan, 2007; Stenglich & Bekele, 2009) have not sufficiently examined the central roles of pastoral women in livelihood transformation or how these roles are evolving. Accordingly, this study aims to explore how gender roles and relationships within the Gabra pastoralist community in the Gomole and Moyale districts of the Borana Zone in southern Ethiopia are influenced by women's participation in income-generating activities, specifically the marketing of camel milk.

2. Material and Methods

2.1. Study area description

Gomole and Moyale districts are in the Borana Zone of the Oromia Regional State, southern Ethiopia. The two districts lie approximately 40 km and 203 km, respectively, from Yabello town, the administrative capital of the Borana Zone. Gomole district is bordered to the north by Fincawa district, to the south by Yabello district, to the east by Arero district, and to the west by Elwaye district (see Figure 1 for details). Moyale district is bordered to the south by Kenya, to the west by the Somali Region, to the southeast by Dire district, and to the east by Guchi district.

Administratively, Gomole district has 14 kebeles (the smallest administrative divisions below the district level): Surupha-Magala, Kella-Qufa, Haro-Bake, Abbunu, Buya, Surupha-Badiyya, Bildim, Tulla-Wayyu, Dasse-Gora, Dambala Saden, Harboro, Tulluqobo, Selle, and Dhakabarru. By contrast, Moyale district comprises 10 kebeles, namely Haramsam, Kabana'a, Goro Bute, Mado Migo, Tuka, Koticha-Tiri, Malab, Mudhi-Ambo, and Moyale-Magala (Moyale town). For this study, Kabana'a kebele from Moyale district and Surupha-Magala kebele from Gomole district were purposively selected, as these kebeles are home to a substantial proportion of Gabra pastoralist women engaged in camel milk marketing.

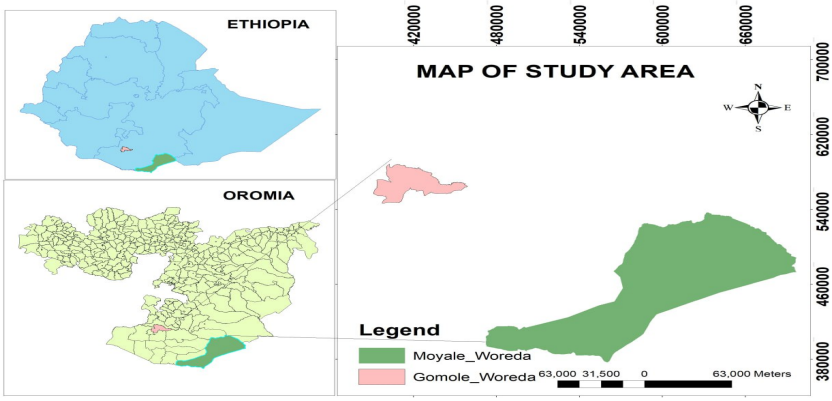

Figure 1: Map of the Study Area

According to Alemayehu and Hizekeal (2022), the Gabra pastoralists are part of the wider Afaan Oromo–speaking camel pastoralist groups who inhabit northern Kenya and southern Ethiopia. The Gabra is known as Gabra Migo in southern Ethiopia and Gabra Malbe in northern Kenya (Soga, 2006; Alemayehu & Hizekeal, 2022). For centuries, livestock rearing has constituted the primary economic activity of the Gabra pastoralists (Soga, 2006). As pastoralists, they depend largely on sheep, goats, and camels, as well as a limited number of cattle. The Gabra are predominantly camel herders, and the shared beliefs and moral values governing animal care underpin social relationships within the community. With an estimated population of 120,000 camels, Gomole district possesses the largest camel herd in the Borana Zone (Gomole District Pastoralists Development Office, 2023).Climatically, Gomole and Moyale districts are characterized by semi-arid conditions, with annual rainfall ranging from 250 to 600 mm. Rainfall occurs in two distinct seasons: the main Ganna rainy season, which extends from March to the end of May, and the shorter Hagayya rainy season, lasting from September to the end of November (Ethiopian Meteorological Agency, 2021).

2.2. Methods of data collection and analysis

The study was conducted in the Gomole and Moyale districts of the Borana Zone Administration, Oromia Regional State, southern Ethiopia, from February 10 to April 1,

2023. Qualitative data collection methods, including key informant interviews, focus group discussions (FGDs), and direct observation, were employed to capture participants' interpretations and perspectives. These qualitative approaches are particularly valuable because they provide insights into the processes underlying observed outcomes and enable the examination of changes in people's views (Bernard, 2002). Purposive sampling was employed to select participants for the key informant interviews and focus group discussions. Participants were women who were directly involved in camel milk marketing. The selection criteria included experience in camel milk marketing, voluntary participation, knowledge of gender roles, and length of residency in the study area.The use of a purposive sampling strategy, combined with the careful selection of participants based on predefined criteria, ensured a comprehensive exploration of the role of Gabra pastoralist women in camel milk marketing. This approach enabled the capture of diverse perspectives while maintaining a focused and efficient data collection process, thereby facilitating the achievement of data saturation. Key informants were selected because of their in-depth knowledge and direct experience related to the research topic. Given the complexity of the pastoralist lifestyle and the nuanced nature of gender roles within the Gabra community, key informant interviews were particularly valuable for understanding the cultural and socio-economic contexts shaping women's involvement in income-generating activities.

Accordingly, key informant interviews were conducted with a wide range of participants, including Gabra pastoralist women involved in camel milk marketing and officials from relevant government offices who possessed first-hand knowledge of the issues under investigation. In total, 19 key informants were interviewed: two government officials from the Cooperative Promotion Offices of Gomole and Moyale districts (one from each district) and 17 camel milk vendors who were members of the Gomole Tesson Naga and Migo Moyale camel milk marketing cooperatives.According to Krueger and Casey (2008), focus group discussions (FGDs) help researchers uncover new aspects and insights related to a study, as participants collectively contribute richer and more diverse perspectives. Following the selection of informants, two FGDs were conducted with purposively selected Gabra pastoralist women who are members of camel milk marketing cooperatives in Surupha town, Gomole district, and Moyale town, Moyale district. Each FGD session had eight participants. This sample size is manageable, ensuring that every participant can contribute while allowing diverse viewpoints to emerge. Moreover, the two districts exhibit similar socio-economic conditions regarding camel milk marketing among the Gabra community, allowing a single FGD from each district to generate rich data without substantial loss of diversity in perspectives. Overall, the use of key informant interviews and FGDs, combined with purposive sampling and appropriate group sizes, significantly enhanced understanding of gender roles and the dynamics of income-generating activities among Gabra pastoralist women involved in camel milk marketing. Direct observations were conducted in Surupha town, Gomole district, and Moyale town, i.e., to examine daily

tasks and activities related to camel milk marketing and to triangulate the findings from the key informant interviews and FGDs.

The data gathered through key informant interviews, FGDs, and direct observation were categorized and analyzed in accordance with the study's objectives using a qualitative thematic analysis approach. Thematic analysis is a systematic technique used to identify, analyze, and report themes in the data, generating categories and sub-themes. The identified themes included: (1) gender roles and income-generating activities, (2) economic implications of camel milk marketing, (3) impacts of camel milk marketing on gender roles and relationships, and (4) challenges faced by Gabra women in camel milk marketing. Data saturation was achieved when no new themes emerged during the FGDs, indicating that the data sufficiently addressed the research objectives. Recurrent patterns and perspectives across the discussions confirmed that the sample size was adequate, and the consistency of responses across both FGDs demonstrated that sufficient information had been collected to comprehensively cover the scope of the inquiry.

To conduct research on Gabra pastoralist women involved in camel milk marketing in Gomole and Moyale districts of the Borana Zone, ethical considerations were prioritized. Informed consent was obtained from all participants prior to data collection. This involved explaining the study's purpose, the voluntary nature of participation, and the right to withdraw at any time without consequences. Participants received information in a language and format they could understand, ensuring their ability to make an informed decision regarding participation. To maintain confidentiality, all identifiable information was anonymized, and data were coded to protect participants' identities.The researchers acknowledged their positionality as outsiders to the Gabra community and as individuals navigating a male-dominated social context. To navigate potential gender dynamics, female community leaders were engaged to facilitate introductions and establish credibility. The researchers also prioritized women's voices during discussions, remaining attentive to cultural expressions of gender roles and encouraging participants to articulate their experiences freely. These measures aimed to uphold participant agency, mitigate discomfort, and empower participants to share their perspectives confidently.

3. Results and Discussion

3.1. Gender roles and income generating activities

Gender roles are the socially constructed norms that define expected behaviors for men and women (Levesque, 2011). They are rooted in the gender binary and shaped by societal perceptions of femininity and masculinity, reflecting characteristics considered natural or desirable for women and men. According to Haile (2008), the ways boys and girls are raised and how they perceive themselves as adults are influenced by socially imposed cultural norms, values, attitudes, and behaviors.

Among pastoralists, gender roles are expressed through activities and responsibilities that shape access to and control resources. Among the Gabra pastoralists, these socially imposed roles define the fundamental responsibilities of the family unit, with clear distinctions between the roles of men and women. Informants indicated that women assume responsibility for household and reproductive tasks, including fetching water, gathering firewood, feeding calves, constructing and maintaining homes, caring for children, and milking livestock. Notably, only women take on the roles of both building and maintaining homes, in contrast to other regions of Ethiopia where men often undertake house construction. Conventionally, men are responsible for herding and managing livestock. The International Labour Organization (ILO, 2008) asserts that the reproductive and productive activities undertaken by women contribute to a double burden, limiting their time for other pursuits and delaying their visibility and recognition in society.

The relationship between gender roles and income-generating activities is particularly important for understanding camel milk marketing among the Gabra pastoralists. Women are gradually expanding beyond household duties to establish themselves as trade vendors, sometimes becoming the sole providers for their families. Gashaw (2015) notes that the growth of income-generating activities and commercialization has had significant and differential impacts on men and women. This study revealed that a remarkable aspect of livelihood transformation among the Gabra pastoralists is the ability of women to manage camel milk marketing enterprises effectively while fulfilling their routine gender roles. Consequently, Gabra pastoralist women can engage in income-generating activities outside the home, although this also results in a disproportionate share of household responsibilities.

Overall, women's contributions are critical for household sustainability and resilience, even as men continue to control larger assets. These findings underscore the necessity of gender-sensitive approaches to economic development in pastoralist societies. To reduce the pressures associated with gender roles, interventions should focus on enhancing income-generating opportunities, reducing vulnerability, and improving food security for pastoralist women.

3.2 The beginning of the camel milk marketing

Camel milk represents a vital source of income for Gabra pastoralist communities, helping them meet their basic needs and maintain food security. In Gomole district, camel milk marketing began with women collecting milk from nearby villages and satellite camps to sell in Moyale town via agents. Camel milk marketing agents continually adapt to challenges through socially structured practices, responding to local conditions and available resources. Each agent operates independently, purchasing milk from specific sellers in villages with whom they liaise. Sellers in Surupha town and surrounding areas, like those in rural Gomole district, rapidly expanded their businesses, strengthening the local dairy industry. The introduction of

camel milk marketing demonstrates Gabra women's capacity to adapt to changing environmental and economic conditions in alignment with their resource base.

According to the Gomole District Cooperative Promotion Office (Nori, 2023), approximately 5,000 liters of camel milk were commercially available per day during the main Ganna rainy season in 2023, and about 3,500 liters per day during the Bonna dry season. Moyale town serves as the economic center of the Borana Zone and has a growing middle-class population, creating exceptionally high demand for camel milk. Consequently, Moyale's camel milk market dominates the Borana Zone, accounting for over 90 percent of milk sales (Nori, 2023). Key informants and FGD participants attribute this dominance to both the Gabra pastoralists' market orientation in the Gomole and Moyale areas and the strong local demand in Moyale town. To improve marketing strategies, Gabra women established the Gomole Tesson Naga camel milk cooperative and developed transport links to deliver milk to Moyale. This cooperative represents a significant step in formalizing the camel milk trade. The chairwoman of Gomole Tesson Naga reported:

On March 9, 2014, Gabra women in Surupha town and neighboring kebeles established the Gomole Tesson Naga camel milk cooperative through their own initiative. The cooperative rents a truck, locally known as ISUZU, which delivers camel milk daily to Moyale. Milk containers, designated for individual traders, are loaded onto the truck, which departs from Surupha town each morning at approximately 9:00 a.m. The truck returns on subsequent days with empty containers and the proceeds from sales. Most of the milk is sold within the Kabana'a suburb of Moyale City, home to many Gabra communities. The cooperative currently has a total of 2,140,000 ETB and 100 members, each contributing 50 ETB weekly.

Source: Authors Fieldwork (2023).
Figure 2: Showing the Members of Gomole Tesson Naga Camel Milk Cooperative Conveying Camel Milk to Moyale.

The results indicate that the Gomole Tesson Naga camel milk cooperative generates higher revenue from sales in Moyale town than from neighboring towns such as Bule-hora and Yabello, primarily due to the higher price of camel milk in Moyale. Members of the cooperative in Gomole district collect milk from camel satellite camps in Camme Kebele of Dugda-dawa district in the West Guji Zone, as well as from neighboring kebeles including Bildim, Tulla-wayyu, and Tullu-qobo, and from individual pastoralists. Depending on the distance from Surupha town, the milk is transported by donkey or motorcycle to the town. To preserve freshness, milk is collected in jerry-cans fumigated with smoldering Oliver and Badana tree wood, which reduces microbial load, extends shelf life, and imparts a distinct flavor. Income from milk sales is shared between the sender and their agents in Moyale town. The cooperative also employs a secretary to monitor the weekly savings of each member. As one discussant explained; "The progress of the Gomole Tesson Naga camel milk cooperative demonstrates the growing formalization of the business following increased demand in Moyale city. To expand the market and revenue, our cooperative actively supports the implementation of laws and regulations governing the camel milk trade." According to this study and previous research (Alemu *et al*., 2022; Nori, 2023), women engaged in income-generating activities not only contribute to household welfare but also help stabilize consumption patterns, reduce livestock sales, diversify income sources, and mitigate exposure to economic shocks. Therefore, diversification in the dairy sector should be understood not merely as a strategy for accumulation but primarily as a survival mechanism in response to deteriorating economic conditions.

3.3. Impacts of camel Milk marketing on gender Role and relations

The increase in income-generating activities and the resultant commercialization impacts men and women differently, influencing gender relationships. The gradual transition to alternative livelihoods is a key factor that significantly shapes the roles and interactions of men and women. Although pastoralists may not have traditionally engaged in financial transactions, Flintan (2000) demonstrates that they have historically maintained diverse livelihoods. The local context—including participation in income-generating activities and preexisting gender norms—shapes how camel milk marketing influences women, men, and their gender relations. Women's participation in income-generating activities in the study area enhanced their daily income, social status, influence within local communities, impact on families and society, and self-esteem. The findings indicate that, following women's engagement in camel milk marketing to supplement household income, their roles and relationships within Gabra pastoralist communities underwent notable changes. According to Alemayehu *et al*. (2023), women's diverse economic activities as traders were crucial to the effectiveness of pastoralism as a production system.

Gender roles among Gabra pastoralists have evolved in response to shifting economic needs, climatic change, and social dynamics. The effects of drought and climate change are intensifying, prompting men and women to differentiate their roles while

collaborating in innovative ways. Research by Nori (2006) demonstrates that frequent droughts have created circumstances in which women's income-generating activities are essential, providing pastoralist women with tangible benefits. Camel milk sales in Gomole and Moyale districts provide a subsistence income that supports daily household expenses, enhancing women's self-esteem and status within their households and communities.

The women reported that their relatively new roles as camel milk sellers enabled them to participate in the public sphere, rather than being confined to domestic responsibilities as in the past. Steglich and Bekele (2009) note that women have become more engaged and visible in economic activities, earning their own income, while men have experienced reductions in livestock holdings due to climate change and associated factors. Previously, cattle sales were an uncommon source of income; currently, camel milk sales provide a steady revenue stream, offering greater financial flexibility during emergencies. The study findings suggest that these developments have promoted greater gender equality and expanded opportunities for Gabra women. This is illustrated by the following statement from a key informant in Kabana'a Kebele, Moyale district.

> "My income from vending camel milk is now my sole source of livelihood. My supplier in Gomole district (Surupha town) provides me with 60 liters of camel milk daily. Once I receive it, I sell it to my clients and negotiate a profit with the supplier. While I am busy selling camel milk, my husband takes care of our two children at home. Occasionally, he prepares meals, fetches water, and even cleans the house. I have covered all of my family's expenses and have even purchased several goats and lambs with the income from camel milk sales."

According to Nori (2006; 2023), the most transformative strategy to enhance women's economic empowerment and meaningful gender equality is for women to participate in income-generating activities. It increases women's economic capacity while giving broader advantages to families. Thus, the astounding change in gender roles among Gabra pastoralists over the past few years can be attributed to women's willingness and effort to try new livelihoods and escape from poverty. Women working in the camel-milk trade are now financially independent since they make their own income without relying on their spouses. As a result, Gabra women are gradually leaving the home, either by choice or necessity, to pursue entrepreneurial opportunities, paving the way for changes in gender roles and relationships. Given that these changes are influenced by a variety of factors, including socioeconomic ones, changes in these domains may also result in changes in gender roles and responsibilities (Anderson *et al*. 2012).

In Ethiopia's southern lowlands, particularly in the Borana zone, the camel's economic potential, as well as its comparative advantages over cattle and other ruminants in terms of adaptation to difficult climatic circumstances and long lactation period, is

becoming increasingly acknowledged. Because of alleged nutritional benefits, fresh camel milk is in considerable demand in Moyale town markets. However, its significance in income generation is relatively new, since it was frequently used as a gift to develop and sustain family ties and social support systems among Ethiopian Gabra pastoralists and other East African pastoralist communities. The selling of camel milk in Gomole and Moyale districts is growing and becoming an important resource for the economic prosperity of many Gabra pastoralists. The study's findings elucidate that camel milk marketing plays an extraordinary role in local food security, providing a consistent income for pastoralists, a valuable source of employment for women, and boosting urban inhabitants' access to nutritious food. In the FGD, one woman from Moyale district characterized the economic ramifications of camel milk marketing as follows:

> "My involvement in the camel milk business has enabled me to educate my children and build my own home in Moyale town. Previously, I had never seen pastoralist women in our area constructing homes or covering daily family expenses on their own. Our cooperative, Migo Moyale, was established in February 2014 with 23 members; it currently has 60 members. The participation of Gabra women in the camel milk business has shifted the perception that men are the sole providers of household income in our community."

The study indicated that camel milk marketing is a multifaceted process, reflecting the highly diversified nature of the pastoralist economy and its susceptibility to market dynamics. As discussed in the preceding section, Gabra women who sell camel milk have achieved financial independence, enabling them to supplement their pastoralist livelihoods and increase household income. The revenue generated from camel milk sales is managed to meet family needs, thereby enhancing women's autonomy and their respect within both the household and the wider community. Furthermore, focus group participants in Moyale town reported that their new roles as milk sellers have significantly increased their prospects for participation in public life, rather than being confined to domestic duties. Conversely, research among Maasai pastoralist women highlights that, although women may exercise control over milk, the corresponding income is often continuously negotiated and contested (Brockington, 2001, pp. 310–311, cited in Flintan, 2011, p. 47). Thus, emerging patterns of trade and economic activity are influenced not only by market forces but also by the evolving autonomy and interdependency of men and women within pastoralist households (Flint, 2011).

In summary, most Gabra women engaged in camel milk trading derive a range of socio-economic benefits, which are critical for enhancing pastoralists' resilience in an era of increasing vulnerability. For many pastoralist communities in southern Ethiopia, camel milk marketing has emerged as a vital source of income, fostering social support networks, communication, and connections that are now integral to local livelihoods. Although challenges such as cultural resistance and limited resource availability persist,

this shift contributes to greater gender equality (Selam *et al*., 2018). Consequently, camel milk marketing initiatives should be prioritized by development organizations as a strategic intervention to support sustainable development in pastoral areas.

4. Conclusion and Recommendations

This study demonstrates that, although Gabra women are increasingly involved in camel milk marketing as a strategy for diversifying household income, their participation is constrained by several structural, environmental, and socio-economic challenges. Key obstacles include limited storage and cooling facilities, limited access to credit, long distances to markets, and high ambient temperatures that accelerate milk spoilage. Inadequate infrastructure in Gomole and Moyale—such as insufficient market facilities and the absence of strategically located milk collection centers—further undermines the efficiency and quality of the camel milk value chain. Seasonal variability also affects supply, quality, and pricing, particularly during prolonged dry periods when production declines. Despite these challenges, Gabra women exhibit resilience and adaptability, and their active engagement in camel milk marketing contributes significantly to household income while challenging perceptions of pastoralist communities as passive in the face of climatic and economic pressures.

The findings underscore the importance of gender-sensitive interventions, as excluding women from development initiatives risks reinforcing existing inequalities. They also highlight the value of experience-sharing opportunities in enhancing women's skills, confidence, and entrepreneurial capacity. While the qualitative nature of the study limits the generalizability of findings beyond the Gabra community, the insights provide a critical foundation for future research. Broader studies employing diverse methodologies are necessary to deepen understanding of women's roles in pastoralist economies and to inform policies that effectively support livelihood diversification. Based on the findings, several interventions are recommended. Basic infrastructure should be enhanced by establishing milk collection centers, cooling and storage facilities, market shelters, and improved road networks to reduce spoilage and improve market access. Women's access to financial services should be strengthened through microcredit, savings schemes, and tailored financial products that facilitate investment in equipment, transportation, and business expansion. Value chain efficiency should be improved by introducing quality standards, promoting proper handling and hygiene practices, and creating mechanisms to stabilize prices across seasons. Gender-responsive development programs should be designed to account for women's roles, constraints, and workloads, ensuring their full participation in training, decision-making, and economic opportunities. Additionally, capacity building and experience sharing should be supported through exchange visits, cooperative groups, and training programs focused on business skills, quality management, and climate-adaptive pastoralist practices.

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Empowering Women in the Commercialization of Ethiopian Agriculture: Insights from Gender Mainstreaming Initiative

Lemlem Aregu*, Kebede Teshome, Temesgen Gebeyehu, Reta Wagary, Kassa Yihun, Kassahun Teka and Dagnachew Lule

Ethiopian Agricultural Transformation Institute (ATI), Gender and Social Team,P.O. Box. 708, Addis Ababa, Ethiopia
Corresponding author* E-mail: lemlem.Aregu@ati.gov.et

Abstract

Given women's substantial contribution to Ethiopian agriculture and their considerable potential as a labor force, it is impossible to transform the sector by ignoring the majority of the workforce. Notably, women account for approximately 43% of the agricultural labor force in developing countries. Similarly, in Ethiopia, women constitute about 40% of the agricultural labor force, either as heads of households (25%) or as family members. However, gender advocacy often faces challenges due to insufficient information to justify the allocation of limited resources toward gender-focused interventions. This paper aims to review gender mainstreaming within the programs of the Ethiopian Agricultural Transformation Institute (ATI), including the Agricultural Commercialization Cluster, Digital Agriculture, and Rural Finance initiatives. It highlights key lessons and best practices for improving women's participation and benefits in the commercialization of agriculture. The assessment involved the analysis of project documents and was complemented by key informant interviews. The findings reveal that ATI's projects incorporate various gender-responsive strategies, such as setting targets for women's participation, enhancing their access to services, and ensuring benefits for women. For example, ATI projects—including 8028 Farmers' Hotline, Agrihub, Horticulture Farmer Production Cluster, Integrated Shallow Ground Water Irrigation Development, and Rural Saving and Credit Cooperatives Capacity Building—have employed gender-responsive approaches. However, women's levels of engagement vary across projects, ranging from 10% in the Mechanization Service Center project to 33% in the 8028 Farmers' Hotline Service. Women's benefits were greater when projects specifically targeted and supported them. Finally, the paper suggests that further investigation is needed to fully assess the impact of project interventions on women's income and overall livelihoods.

Keywords: Agricultural labour force, Gender-responsive strategies, women's participation.

1. Introduction

Gender equality remains an important development goal worldwide, including in Ethiopia and the African region, because it is a foundation for sustainable development, social justice, and inclusive growth. In Ethiopia, women make up about 40% of the agricultural workforce (Simachew *et al*., 2022); however, they continue to have limited access to land, credit, and agricultural technologies. Improving women's

access to these resources and reducing existing gender gaps could significantly increase agricultural productivity and national income.

The 2030 Agenda for the Sustainable Development Goals (SDGs), to which Ethiopia is a signatory, emphasizes the importance of empowering women and girls and ensuring gender equality. Given women's substantial contribution to Ethiopian agriculture and their significant potential as a labour force, it is impossible to transform the sector while ignoring the majority of its workforce. According to USAID (2020), women account for 49.7% of the workforce. Notably, women represent approximately 43% of the agricultural labour force in developing countries (FAO, 2022). Similarly, women's contribution to Ethiopian agriculture exceeds 40% of the agricultural labour force, and they head approximately 25% of all farming households in the country (Simachew *et al*., 2022). However, gender advocacy often faces challenges due to insufficient evidence to justify the allocation of limited resources to gender-focused interventions (Quisumbing & McClafferty, 2006).

Despite women's significant contributions to agriculture, gender disparities in agricultural production remain a major barrier to the growth of Ethiopia's agricultural sector (Drucza *et al*., 2020). Women's agricultural productivity is estimated to be up to 30% lower than that of men in Sub-Saharan Africa (Aguilar *et al*., 2015) and about 11% lower in Ethiopia (UN Women, 2019). This disparity is not due to inefficiency among women farmers, but rather to structural constraints that limit their productivity and participation, particularly in the production and marketing of high-value agricultural commodities. Limited access to and control over resources, services, and finance are among the key challenges. Women also experience inequitable access to agricultural inputs, including family labour, improved crop varieties, livestock, pesticides, and fertilizer. Equalizing women's access to agricultural inputs particularly time-saving technologies and increasing returns to these inputs are therefore critical to closing gender gaps in agricultural productivity.

Agricultural commercialization in Ethiopia has the potential to empower women, create employment opportunities including for young women and improve access to nutritious and diversified diets for households and smallholder farmers. It can also increase women's incomes, strengthen household economies, contribute to overall economic growth, and enhance food production and consumption of nutritious foods. Aligned with its mandate, the Ethiopian Agricultural Transformation Institute (ATI) has implemented approximately fifty-five projects under various programs, of which fifteen are currently active, while the majority have been completed and transferred to long-term stakeholders. Despite the expectation that gender mainstreaming should be integrated across ATI's programs and projects, no comprehensive assessment or systematic documentation of these gender integration efforts has been conducted for learning or scaling purposes. This review paper therefore aims to evaluate ATI's project interventions in terms of gender inclusiveness, assess the benefits women have gained from these projects, and extract valuable lessons for future scaling.

Currently, most active projects are implemented under the Agricultural Commercialization Clusters (ACC I), Digital Agriculture, and Rural Finance programs. The ACC program aims to enhance agricultural production and productivity in selected geographic areas and commodities and to accelerate the transition of smallholder farmers from subsistence to commercial, market-oriented production systems, while promoting environmental sustainability and social inclusion. According to the Program Appraisal Document (PAD), the ACC I is designed to contribute to six outcomes, one of which is improved engagement of women and youth in agricultural production and marketing decision-making across value chains. Similarly, the Digital Agriculture and Rural Finance programs identify women farmers as key target groups for the provision of digital and modern agricultural information and services.

Considering women's limited access to and control over critical resources such as land and finance, effectively engaging them in market-driven agriculture—particularly within commercialization clusters and digital service frameworks—requires the adoption of gender-sensitive and gender-responsive strategies. Accordingly, the objective of this paper is to assess the extent to which ATI's programs and projects are gender-sensitive and responsive, examine how women farmers have benefited from these interventions in recent years, and identify key lessons learned, best practices, and the opportunities and challenges women face during implementation.

2. Materials and Methods

2.1. Data Collection and Analysis

A combination of qualitative and quantitative research methods was employed to assess gender mainstreaming practices at the Ethiopian Agricultural Transformation Institute (ATI). Both primary and secondary data collection methods were adopted for this assessment. The assessment relied primarily on a review of monitoring and evaluation reports from projects implemented under ATI's Agricultural Commercialization Clusters (ACC), Digital Agriculture, and Rural Finance programs. This document review was complemented by key informant interviews (KIIs) with project staff and by analysis of the ACC Terminal Report (2024). Relevant program- and project-level documents were reviewed to assess project achievements in terms of reaching women beneficiaries and enhancing the benefits they derived from project interventions. The documents reviewed included the ACC Program Appraisal Document (ACC-PAD), the ACC I Performance Report (2021–2024), Digital Agriculture and Rural Finance program reports (2019–2024), and the ACC I Terminal Report (2024).

Key informant interviews were conducted using semi-structured questionnaires. Accordingly, checklists were distributed to project leaders and technical experts responsible for projects under the ACC, Digital Agriculture, and Rural Finance programs. In total, eight key project experts were interviewed. All respondents completed the checklist and were subsequently contacted either in person or virtually for further discussion and clarification based on their responses. The assessment focused on currently active projects within ATI. Out of the fifteen active projects,

eleven projects—namely IVS, 8028 farmers Hotline, NMIS, G-FPC, MSC, AoSS, H-FPC, Agri-HUB, ISGWID, CBSP, and RUSACCO—were selected for review. Specifically, seven projects were drawn from the ACC program, two from the Digital Agriculture program, and two from the Rural Finance program. These projects were purposively selected for in-depth assessment of gender sensitivity, responsiveness, and outcomes.Qualitative and quantitative data obtained from document reviews and key informant interviews were analyzed using content analysis and descriptive statistical methods, respectively. The analysis was organized around a combination of pre-coded and emergent thematic and sub-thematic categories. Key themes included women-preferred agricultural commodities; gender-related challenges; gender division of labor; differences in access to and control over resources and services; gender-sensitive indicators; gender-responsive interventions; gender analysis; and gender budgeting.

3. Results and Discussion

The assessment results indicated that several projects implemented under ACC I (including the Horticulture FPC and One-Stop Shop initiatives), as well as projects under the Digital Agriculture and Rural Finance programs, have made efforts to reach women farmers by engaging them at different stages of project implementation. However, the level of women's participation varied considerably across projects, ranging from 10% in the Farmers Production Cluster–Grain (FPC-G) project to 33% in the 8028 Farmers' Hotline project. As indicated in Figure 1, projects s
uch as the 8028 Hotline, Horticulture FPC, Integrated Shallow Groundwater Irrigation Development (ISGWID), and the National Market Information System (NMIS) reached relatively higher proportions of women participants, with participation rates ranging from 30% to 33%. Variations in women's participation levels and the benefits they derived from different projects were influenced by several gender-related factors. These included the suitability of targeted commodities to women's needs and priorities; the extent to which project interventions addressed women's specific constraints; the breadth of project activities across different stages of the value chain, which potentially offered greater opportunities for women's engagement; and the type of technologies and services provided. The assessment results also showed a slight improvement in projects' outreach to women and in gender-disaggregated reporting compared with the 2022–2024 period. This improvement was observed following ATI's deployment of gender-sensitive planning tools that require projects to plan and report using gender-disaggregated data.

Women's access to mechanization and digital tools has been shown to enhance efficiency and reduce labor burdens, allowing time for other productive activities. However, studies indicate that women's access to agricultural machinery is often constrained by financial limitations, lack of training, and inadequate support services (Moss & Kelly, 2015). Similarly, in digital agriculture, women's adoption of technologies is hindered by low digital literacy, limited access to digital devices, and gender biases in technology design and implementation (Cameron & Kambugu, 2020). Despite these challenges, targeted interventions—such as tailored training programs and financial

support mechanisms—have demonstrated positive impacts on productivity and women's empowerment in agriculture. When compared with these findings, Ethiopia's ATI programs, which emphasize mechanization and digital solutions, demonstrate areas of progress while also revealing gaps in addressing gender-specific needs and barriers. Overall, the ACC, Digital Agriculture, and Rural Finance programs provide multifaceted benefits to smallholder farmers and other value chain actors, including women. These benefits stem from market-driven and geographically targeted approaches supported by essential services such as capacity building, improved access to finance, and the provision of digital information, technologies, and agricultural inputs.

3.1. Comparison of women's participation by commodity/project

Women and men often have different needs and priorities regarding commodity selection and production decisions. For example, women farmers tend to prefer commodities that can be easily cultivated around the homestead or in backyard plots using a limited labor force, whereas men typically favor commodities with higher yields and greater income-generating potential. These differences significantly influence engagement levels, preferences, and motivation to participate in agricultural interventions. Horticultural crops such as Onions, Avocados, and Mangoes are generally more accessible for women to cultivate, as they can be grown in home gardens or backyard plots. This is advantageous because such crops are commonly used in daily household consumption and can be produced close to the home. Research indicates that these practices enhance women's participation in agriculture, as they do not require large-scale farmland and can be managed within the domestic sphere (FAO, 2020). This finding aligns with ATI's experience, where the Horticulture Farmers' Production Cluster (HFPC) demonstrated relatively stronger performance in reaching women, with female beneficiaries accounting for approximately 32% of participants. In response, ATI supported the establishment of women's seedling production and marketing groups under the horticulture FPC in southern Ethiopia to produce Tomato, Avocado, and Mango seedlings.

In contrast, the assessment found that women's participation in Cooperative-Based Seed Production (CBSP) was limited to 17%. Seed production requires access to farmland, over which women often have limited control and decision-making authority. This constraint makes it difficult for the Farmers' Production Cluster–Grain (FPC-G) project to reach women and restricts their engagement in grain production and marketing. Moreover, the proportion of direct women beneficiaries in FPC-G remained at only 19%, falling short of the intended target of 30%. The sampled projects under this assessment covered diverse intervention areas along agricultural value chains, ranging from production to marketing, ultimately reaching consumers. Projects targeted different agricultural commodities, including grains, horticultural crops, and livestock, and employed varied production systems, marketing arrangements, and technologies. For instance, the Integrated Shallow Groundwater Irrigation Development (ISGWID) project aimed to improve access to irrigation through the

development of shallow groundwater sources for household-level, small-scale irrigation. Improved access to irrigation near homesteads enabled women to produce high-value crops for multiple purposes, including household consumption, income generation from surplus production, and reduced time spent fetching water. These outcomes expanded opportunities for women to increase productivity and income, thereby enhancing food security and self-sufficiency.

3.2. Technologies and Services Provided

Enhancing technologies and services from women's perspectives significantly improves their conditions and opportunities. For example, the introduction of labor-saving technologies—such as improved machinery for land preparation and threshing—has had a transformative effect on women's agricultural engagement. Through initiatives such as Mechanization Service Centers (MSCs), these technologies have reduced the time and physical effort required for labor-intensive tasks, enabling women to reallocate their time and energy to other productive activities (FAO, 2021; World Bank, (2022). Similarly, the integration of digital agriculture tools, exemplified by the 8028 Farmers' Hotline Service, has benefited women by providing gender-specific messages and gender-focused advisory services. This service delivers essential information and guidance, enabling women to improve agricultural practices, enhance nutrition outcomes, and strengthen market engagement. Evidence from IFAD (2020) and FAO (2022) supports these findings. By improving access to information and resources, such technologies enhance women's productivity, support informed decision-making, and contribute to improved economic outcomes and social status (World Bank, 2021).

3.3. Diversity of Interventions, Gender Visibility, and Integration

The projects assessed in this review are diverse and have implementation periods ranging from four to eleven years. Most are at their final stages—particularly those under ACC I—or are nearing completion, while the remaining projects are expected to conclude within the next two to three years. Therefore, it is important to assess and learn from the experience of gender mainstreaming within ATI's ACC I, Digital Agriculture, and Rural Finance programs. Such an assessment will also enable ATI to better understand how gender issues are addressed across different contexts of the agricultural commercialization process and to inform the design and implementation of upcoming projects and programs.

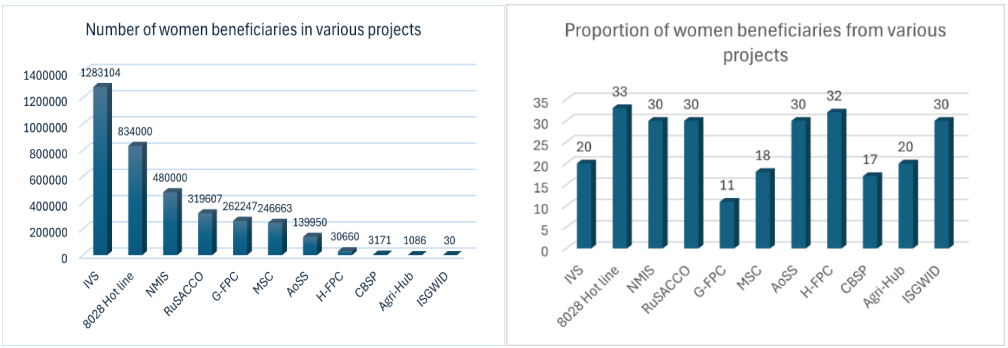

Figure 1**:** Number and proportion of female participants in the projects' interventions

Many projects focus on providing multiple agricultural inputs and services, including machinery, improved seeds, fertilizers, and agrochemicals, through both conventional and digital delivery methods. These interventions recognize that women and men face distinct challenges and opportunities in agricultural production and marketing, which shape their needs, priorities, and expectations. Understanding these gender-specific differences is essential for tailoring services effectively and enabling women and men to derive equitable benefits from agricultural advancements.

3.4. Window of entry points to women's inclusion in the projects

To include women effectively in agricultural projects, it is essential to base interventions on a comprehensive gender analysis that identifies their specific needs, barriers, and opportunities. Such analysis ensures that programs are designed to address women's constraints appropriately. However, many projects fail to integrate gender analysis at key stages of the project lifecycle. Recent assessments revealed that only three of the eleven sampled projects CBSP, 8028 Farmers' Hotline, and NMIS (approximately 28% of projects) conducted gender analysis during implementation, compared with FAO's recommended standards (FAO, 2022). This oversight hampers efforts to reach and engage women effectively, thereby limiting the overall inclusiveness and success of the projects (World Bank, 2021; IFAD, 2020). To maximize benefits for women, interventions must target their specific needs and constraints. Women often face limited access to agricultural inputs, so providing targeted provisions can help alleviate these challenges (FAO, 2021). Implementing labor-saving technologies and mechanization is another critical entry point, as these innovations reduce women's workloads and allow them to allocate more time to productive activities (World Bank, 2022). Although women typically have limited control over grain production and marketing, they play a vital role in seed management, including quality control, storage, and selection. In line with this, ATI established Mechanization Service Centers (MSCs) that provide labor-saving technologies, such as threshers and harvesting machines. The assessment revealed that 18% of women benefited from these labor-saving technologies.

Programs can further support women by promoting horticultural crops, which are easier for women to manage and can be grown in backyard gardens where women have better access and control (FAO, 2022). For example, ATI's H-FPC project promoted the production and marketing of horticultural crops, including Avocado and Tomato seedlings, targeting women farmers. Similarly, the ISGWID project enabled women to cultivate various vegetables and high-value crops in backyard gardens using small-scale irrigation, enhancing opportunities to increase income. Providing women with marketing information can also improve income opportunities, as they often lack access to such data (IFAD, 2021). Digital and automated systems, including financial technologies, reduce transaction costs, prevent fraud, and ensure timely reconciliation (World Bank, 2022). Assessment results from key informants and document reviews indicated that the 8028 Farmers' Hotline service reached a total of 6.9 million users, including 2.5 million farmers within the ACC, with women accounting for 33% of beneficiaries, while the NMIS project reached 30% of women through market information interventions. Furthermore, disseminating information on topics relevant to women, such as nutrition and horticultural practices, supports both economic and social empowerment (FAO, 2022). Accordingly, ATI delivered push messages on nutrition to women and their families through the hotline service.

3.5. Women benefited from projects' intervention

Key informant interviews revealed that most projects aimed to benefit 30% of women in their interventions, and many exceeded this target. According to the ACC I terminal reports (2024), significant achievements were recorded in improving women's access to information, finance, inputs, markets, and capacity-building services. For example, the 8028 Farmers' Hotline Service project initially had 27% female users during its pilot phase, which increased to 33% by the final stage (Terminal Report, 2024). As illustrated in Figure 1, approximately 24,663 women (18% of total beneficiaries) utilized mechanization services until 2024. During the same period, 1,283,104 women accessed financial services through the input voucher system, representing 13% of total beneficiaries. Additionally, around 834,000 women, accounting for 33% of total female beneficiaries in ACC, received advisory services via the 8028 Farmers' Hotline until 2024. Regarding capacity-building initiatives, over 1,126 women benefited from the One Stop Shop project in 2020. Moreover, 30% of women benefited from the ISGWID project, and 11% from the FPC-Grain project. Overall, monitoring and evaluation reports and terminal reports from ACC demonstrate notable achievements in women's inclusion and benefits across various projects (Figure 1).

3.6. Strategies for gender integration

Key informants reported several strategies to enhance women's engagement with and benefits from their projects, including tailored promotional activities with women's organizations (e.g., NMIS project), improved access to agricultural inputs with special attention to women (e.g., IVS, AoSS), partner orientation to support women (MSC), increasing female inclusion in project planning (ISGWD), and raising awareness about

gender-inclusive practices. They also promoted women's roles in seed production through training and leadership positions, provided labor-saving equipment, organized women into production clusters with the necessary support, set specific targets for female participation in leadership positions in the FPC, and demonstrated women's superior loan repayment rates, among other outcomes. FAO (2020) and World Bank (2021) also confirmed that these strategies have been effective in fostering greater involvement of women and associated benefits in agricultural projects.Top of Form

3.7. Working on improved technologies as an opportunity for gender integration

As ATI is working on various improved and modern technologies in facilitating access to inputs and their utilization, to which women have limited access, many women benefited from such services. For example, the IVS and e-voucher have streamlined the process of input purchases, improved access to credit, and encouraged savings in rural communities, including women, with 385,000 and 507,000 women benefiting in 2021 and 2022, respectively. Smallholder farmers, including women, have begun planning their input purchases and related expenses for planting seasons. A considerable proportion of female farmers (19–42%) have accessed inputs through AoSS. Such an approach demonstrates that an improved extension approach addresses women's limited access to inputs and other services.

4. Conclusion and Recommendations

Effective gender mainstreaming is critical for advancing agricultural commercialization in Ethiopia. Conducting gender analysis at key stages of the project cycle allows project teams to identify the specific needs, constraints, and opportunities of women and men and to address barriers that limit women's participation and benefits. Integrating these findings into project design and implementation, and regularly updating them, ensures that interventions are feasible, inclusive, and responsive to the diverse experiences of women, considering factors such as age, marital status, rural–urban location, and socioeconomic status. To monitor progress and evaluate impact, it is essential to develop gender-sensitive indicators and employ a gender-sensitive Monitoring, Evaluation, and Learning (MEL) system. Longitudinal studies, sex-disaggregated achievement reports, and budgeting reports for gender-related activities will support evidence-based decision-making. A gender-sensitive MEL system ensures that success is measured not only by outputs but also by who participates, who benefits, and who is empowered, thereby promoting equity and inclusivity across agricultural programs.

Investing in women's visibility and participation in agribusiness is also crucial for inspiring other women and demonstrating their capabilities. Scaling up successful experiences through gender-transformative approaches—designed to challenge cultural, social, and traditional norms that hinder women's engagement—alongside gender-responsive and gender-sensitive interventions, can enhance women's benefits and promote inclusive agricultural transformation. Finally, strengthening discussion, advocacy, and enforcement of national and international policies on gender equality, women's empowerment, and land certification will expand opportunities for women

and address persistent challenges. Community engagement, awareness campaigns, partnerships with local organizations, and active policymaker involvement are recommended to institutionalize gender mainstreaming in agricultural programs and ensure that gender equality remains a priority in national development plans.

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Variations in Livelihood Strategies and Socioeconomic Benefits Between Traditional and Improved Agroforestry Systems in Bale Zone, Southeastern Ethiopia

Boja Tilinti[1,2 *], Mesele Negash[3], Zebene Asfaw[1], Teshale Woldeamanuel [1]

[1]Wondo Genet College of Forestry and Natural Resources, Hawassa University
[2]College of Agriculture and Natural Resources, Madda Walabu University
[3]European Forest Institute, Rome, c/o CREA-IT, Via Manziana 30, 00189 Rome, Italy
*Corresponding author: bojatilinti55@gmail.com

Abstract

In developing countries, households employ a variety of livelihood strategies to earn income and meet their basic needs. Homegarden agroforestry (HGAF) systems are one type of land use that supports smallholder farmers' livelihoods. The adoption of new agroforestry technologies and the characteristics of HGAF impacts household livelihoods. This study examined livelihood strategies, socioeconomic benefits of HGAF, and its influencing factors in Bale Zone, Southeastern Ethiopia. A total of 96 home gardeners (48 improved and 48 traditional) were randomly selected among household heads. Data was collected through household interviews, key informant interviews, and focus group discussions. The results reveal that while households with traditional HGAF focus on livelihood diversification, those with improved HGAF implement both agricultural intensification and livelihood diversification equally. Individuals engaged in improved HGAF practices (100% and 91.7%) and traditional HGAF (100% and 41.7%) reported commonly obtaining food and income benefits, respectively. The main obstacles to HGAF profitability were diseases and pests, followed by water shortages, inadequate capacity building, transportation issues, limited market accessibility, and climate change. Supporting households through the dissemination of novel agricultural technologies and the establishment of market linkages is crucial for improving farmers' livelihoods. Further research should explore the other ecosystem services provided by HGAF and identify ways to maximize their benefits.

Keywords: Agricultural Intensification, Improved Homegarden Agroforestry, Livelihood Diversification.

1. Introduction

In developing countries, households adopt various livelihood strategies to generate income and meet their basic needs (Brown *et al*., 2006; Ellis, 2001). These households either diversify their income sources or concentrate on a few of them. A widely used survival strategy and pathway to improve living standards among smallholder farming households is the shift from subsistence farming to the cultivation of annual and perennial crops for commercial purposes (Manlosa *et al*., 2019). Agroforestry systems represent an important land-use approach that enables smallholder farmers to sustain

their livelihoods (Prabawani *et al*., 2024; Yirga *et al*., 2024); Brown *et al*., 2006) while also contributing to long-term ecosystem stability (Bucheli and Bokelmann, 2017). By integrating trees with crops and livestock, agroforestry enhances local livelihoods through diversified outputs, including food, fuelwood, fodder, income, and medicinal and aromatic plants (Muthuri *et al*., 2023; Pandit *et al*., 2019; Hanif *et al*., 2018).

Homegarden agroforestry (HGAF) represents an efficient agroforestry system that simultaneously provides long-term ecosystem services and enhances household financial security (Muthuri *et al*., 2023). According to Calvet-Mir *et al*. (2012), HGAF not only enhances entrepreneurship but also contributes to improved household economic well-being. The biodiversity inherent in HGAF systems enables families to meet their daily needs while maintaining cultural traditions and lifestyles (Jeeceelee and Sahoo, 2022). Reyes-García *et al*. (2012) reported that, despite their small size, homegardens generate high economic returns. Furthermore, studies from Indonesia, Sri Lanka, and Vietnam indicate that HGAF contributes between 20% and 60% of household income (Mohri *et al*., 2013). The importance of HGAF extends beyond income generation, as homegardens directly enhance food availability, nutritional security, and dietary diversity (Duffy *et al*., 2021; Thamilini *et al*., 2019; Galhena *et al*., 2013).

Moreover, HGAF is a practical and efficient approach to addressing land scarcity through the integration of multiple food and income-generating components within relatively small landholdings (Abebe, 2005). A study by Cardozo *et al*. (2015) indicates that HGAF is one of the most productive and promising land-use systems, offering the highest profits and net benefits per hectare. The diversification of annual and perennial plants under HGAF provides higher income compared to monoculture farming. Sales of HGAF products increase household revenue, while the consumption of homegarden produce reduces food and healthcare-related expenses and thus indirectly enhances disposable household income (Naigaga *et al*., 2021; Rajagopal *et al*., 2021; Linger, 2014). These mechanisms illustrate how HGAF contributes to improved household economic well-being. Cash crops such as Catha edulis and Coffea arabica are favored by farmers because they generate substantial income (Terfassa, 2021; Teklu *et al*., 2018).

In Ethiopia, HGAF represents both a widespread agroforestry practice and the most substantial land-use system (Abebe *et al*., 2010; Abebe, 2005), serving more than 20 million people (Borrell *et al*., 2019). Similarly, it is widely regarded as the most appropriate land-use system for sustaining the livelihoods of local communities (Elbakidze *et al*., 2018). Beyond ecosystem services, Ethiopian agroforestry systems supply fuelwood, fruits, timber, spices, income, and animal feed resources (Walden *et al*., 2024; Hafte, 2020; Gebrehiwot, 2017; Negash, 2007). Despite these benefits, homegardeners continue to face persistent challenges, including water shortages, limited access to improved seedlings, gaps in technical knowledge, pests, and diseases, which constrain productivity (Pokwana *et al*., 2021; Cilliers *et al*., 2018; Maroyi, 2009).

The benefits of human-dominated agricultural landscapes increase significantly when smallholders adopt innovative agroforestry technologies (Scudder *et al*., 2022; Quinion *et al*., 2010). Improved forms of traditional agroforestry are gradually emerging, providing higher economic returns along with diversified products (Kay *et al*., 2019; Kassie, 2018). Of particular importance is the fact that improved HGAF within traditional systems—adapted through the integration of high-value cash and cereal crops responsive to land constraints and market demand—allows households to enhance plant species diversity without necessarily compromising food security or dietary diversity (Teklu *et al*., 2018). Evidence from Nepal (Paudel *et al*., 2021) and Vietnam (Sekhar, 2007) also indicates that improved agroforestry systems deliver substantially higher productivity and income per unit of land. Financial evaluations of new agroforestry technologies are therefore essential to determine their feasibility and the likelihood of adoption by smallholders (Scudder *et al.,* 2022).

However, in Ethiopia, there is a lack of well-designed studies assessing the economic benefits of improved HGAF in comparison with traditional HGAF systems. Consequently, the objective of this study was to evaluate and compare the socioeconomic benefits of traditional and improved HGAF in Bale Zone, Southeastern Ethiopia. Specifically, the study aimed to: (a) identify and describe the livelihood strategies of households practicing HGAF (improved and traditional); (b) assess the socioeconomic benefits of HGAF; and (c) identify the factors limiting homegardeners' ability to maximize outputs from their HGAF systems in Bale Zone, Southeastern Ethiopia.

2. Materials and Methods

2.1. Description of study area

The study was conducted in the Dello Menna and Harenna Buluk districts of Bale Zone, Southeastern Ethiopia (Figure 1). The Harenna Natural Forest and Bale Mountains National Park, both of which are rich in flora and fauna, are in Bale Zone near the study districts. The elevation of the study area ranges from 1,380 to 1,580 meters above sea level.

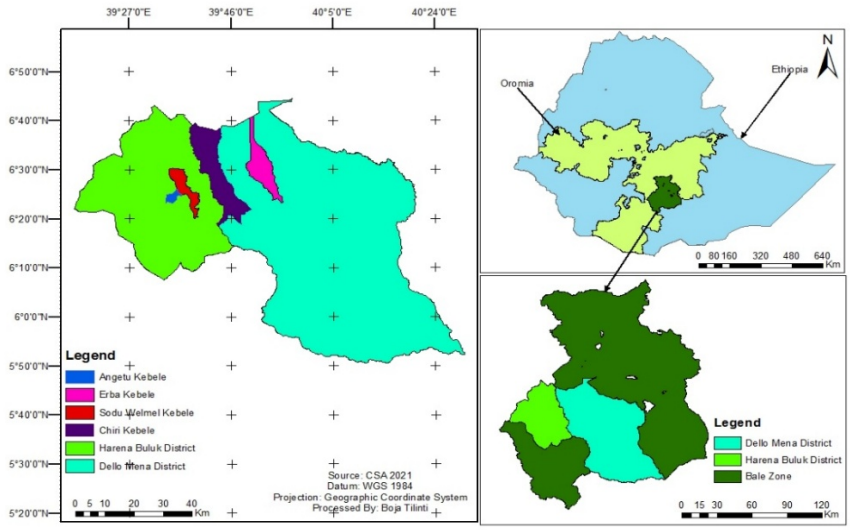

Figure 26: Map of the study area

According to Shigute *et al.* (2023), the study area has an average annual temperature of 17.4 °C and an annual rainfall ranging from 591 to 1,617 mm. The rainfall pattern is bimodal, with a short rainy season occurring between March and April, followed by a longer rainy season from August to October. Nitisol is the dominant soil type in the study area. According to population projections by the Central Statistical Agency (CSA, 2022), the study area had 117,236 residents in Harenna Buluk District and 132,559 in Dello Menna District.

The mainland-use types in the two districts include forest, agriculture, agroforestry, and grazing land. The most common agroforestry systems are homegardens, parklands, woodlots, live fences, and coffee-based agroforestry systems (Mengistu and Asfaw, 2016; Molla and Kewessa, 2015). Fruit tree species such as Musa paradisiaca, Mangifera indica, Persea americana, and Carica papaya are widely cultivated in HGAF systems. Furthermore, native plant species such as Coffea arabica, Croton macrostachyus, Ricinus communis, and Cordia africana are also widespread (Tilinti *et al*., 2024).

Homegarden agroforestry (HGAF) refers to an agroforestry system established around homesteads within delineated garden boundaries, comprising a diverse range of plant species and, in some cases, livestock. Both traditional and improved HGAF practices are present in the study area (Tilinti *et al*., 2024). Traditional HGAF is characterized by households relying primarily on their own experience and indigenous knowledge rather than external inputs. In contrast, improved HGAF involves the use of external inputs such as irrigation systems, access to improved seeds or seedlings, and extension services.

A significant proportion of the population in the study area (87.5%) derives its livelihood from agricultural activities. Households in the Harenna Buluk and Dello Menna districts of Bale Zone engage in the cultivation of annual crops (wheat, barley, maize, and teff), livestock production (cattle, horses, mules, sheep, goats, and donkeys), and their integration with trees. These activities include the production of Coffea arabica, Saccharum officinarum, Catha edulis, fruit trees, vegetables, honey, timber, and other non-timber forest products. In addition, households undertake non-farm activities, such as agricultural wage labor, and off-farm activities, including the collection of Coffea arabica from forests and the sale of Saccharum officinarum, Catha edulis, and fruit products in local markets (BZANRO, 2023).

2.2. Sampling techniques and sample size determination

The study used a multistage sampling approach to identify sample households. First, the Dello Menna and Harenna Buluk districts were selected based on the presence of both traditional and improved HGAF practices. Second, four kebeles (the smallest administrative units in Ethiopia) were selected. Third, the sample size was determined following the method proposed by Kothari (2004).

$$n = \frac{Z^2 * p * q * N}{d^2(N-1) + Z^2 * p * q}$$

Where, n = sample size; N = number of households; Z = the value of the normal variable ($Z_{0.25}$ = 1.96) for a reliability level of 0.95; q = probability of failure (0.5); d = margin error (0.1), and p = probability of success (0.5).

A total of 96 household heads were randomly selected from four kebeles for household interviews, comprising 48 practicing traditional HGAF and 48 practicing improved HGAF. Sixteen key informants were selected using the snowball sampling technique (Angelsen *et al*., 2011). Initially, kebele administrators were requested to nominate four knowledgeable farmers from each kebele with extensive experience in managing and practicing HGAF. These farmers then selected and ranked four additional farmers in each kebele who possessed comparable expertise in HGAF management. Ultimately, the highest-ranked farmers served as key informants during data collection. Key informants categorized homegardeners into three wealth groups—rich, medium, and poor—based on locally defined criteria. In addition, eight focus group discussions (FGDs) were conducted with homegardeners of different age groups and local experts using open-ended questions. In each kebele, two FGDs (one male and one female) were held, with group sizes ranging from 6 to 14 participants (Burnard *et al*., 2008).

2.3. Methods of data collection and Analysis

Semi-structured interviews were conducted to collect information on household socioeconomic characteristics, plant species present in HGAF systems, and their uses. Each sampled household provided data on the occupation of the household head as

well as the primary sources of benefits derived from HGAF. Information on livelihood strategies and the socioeconomic benefits obtained from HGAF—both for subsistence and sale—was primarily gathered through consultations with household members knowledgeable about the HGAF products. Key informant interviews were used to validate information on the role of HGAF in household livelihood strategies and the uses of plant species. In addition, focus group discussions were conducted to collect data on household livelihood strategies and the utilization of plant species within HGAF systems.

Descriptive statistics were employed to analyze household livelihood strategies, HGAF benefits, and the factors limiting the realization of HGAF benefits. Overall HGAF benefits were assessed, including income derived from HGAF, food crops, fuelwood, timber, fodder, and other HGAF-related products.

3. Results and Discussion

3.1. Household livelihood strategies

Livelihood diversification was the most common livelihood strategy for households practicing HGAF in study areas, followed by agricultural intensification, while the migration is unusual (Figure 2). However, households using improved HGAF practice both livelihood diversification and agricultural intensification equally, whereas households using traditional HGAF primarily practice livelihood diversification strategies.

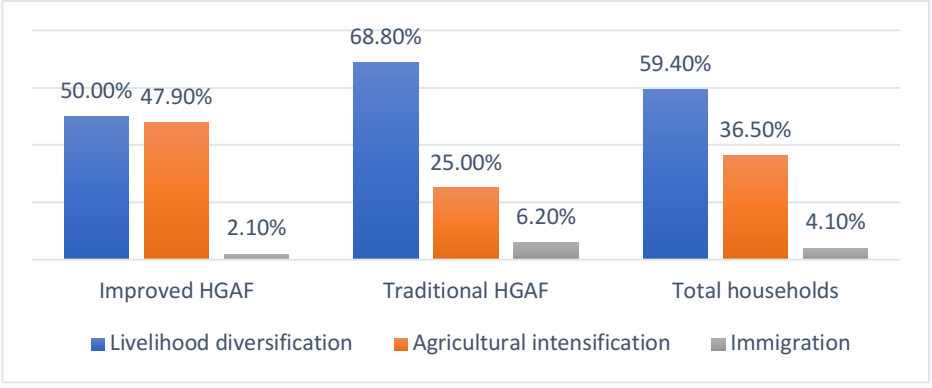

Figure 27. Livelihood strategies of HH practicing improved and traditional HGAF in Harenna Buluk and Dello Menna Districts

The results compare livelihood strategies between households practicing improved and traditional Homegarden Agroforestry (HGAF). Livelihood diversification is significantly higher in traditional HGAF (68.8%) than in improved HGAF (50%), suggesting that traditional households rely on multiple income sources to mitigate risks. Conversely, agricultural intensification is more prevalent in improved HGAF (47.9%) compared to traditional systems (25.0%), reflecting a focus on maximizing productivity. Migration

rates are low in both groups, at 2.1% in improved HGAF and 6.2% in traditional HGAF. These findings highlight the distinct strategies employed by households to achieve livelihood security and emphasize the need for interventions that promote both agricultural intensification and income diversification to enhance household resilience.

3.2. Role of HGAF for household socioeconomic benefits

Food and income were the primary benefits that households derived from HGAF in the study area (Table 1). Among households practicing improved HGAF, food and income were the most frequently reported benefits, at 100% and 91.7%, respectively. In contrast, households practicing traditional HGAF reported food as the main benefit (100%), followed by income (41.7%) and medicinal uses (33.3%). Timber-related benefits were reported less frequently, with 8.3% of traditional HGAF households and 4.2% of improved HGAF households indicating its use.

Table 1**:** Socioeconomic benefits of HGAF in Harenna Buluk & Dello Menna Districts, southeastern

Benefits of HGAF	**Traditional HGAF (%) (n=48)**	**Improved HGAF (%) (n=48)**
Incomes	41.7	91.7
Foods	100.0	100.0
Honey productions	20.8	27.1
Shades	25.0	20.8
Fuelwoods	20.8	16.7
Medicines	33.3	29.2
Constructions	22.9	18.8
Fodders	16.7	20.8
Fences	14.6	16.7
Timbers	8.3	4.2
Ornamentals	12.5	18.8
Aromatics	27.1	22.9

3.3. Factors influencing contribution of homegarden agroforestry to households

Homegardeners in Harenna Buluk and Dello Menna districts face various barriers to realizing socioeconomic benefits from their HGAF. Plant diseases and pests, inadequate water supply, limited capacity building, and lack of transportation were identified as the most significant constraints to expanding HGAF-derived benefits in the study area (Table 2). Specifically, for households practicing traditional HGAF, plant diseases and pests were the primary limiting factors, followed by limited market access and transportation constraints, which hindered the expansion of HGAF products. In contrast, for households practicing improved HGAF, water scarcity was the most critical limiting factor, followed by plant diseases and pests, as well as insufficient training, which restricted the productivity of their HGAF.

Table 2: Factors influencing HGAF contribution to smallholder farmers in Harenna Buluk & Dello Menna Districts.

Limiting factors	**Traditional HGAF (%) (n=48)**	**Improved HGAF (%) (n=48)**
Diseases and pests	41.7	29.2
Water scarcity	0.0	47.9
Lack of training	5.1	22.8
Lack of transportation access	22.9	16.7
Lack of market access	27.1	5.2
Climate fluctuation	16.7	12.5
Lack of credit/finance	11.2	5.2
Lack improved seeds	2.1	25.0
Shortage of lands	6.2	4.2
Crop raiding by wild animals	4.2	4.2

3.4. Households' livelihood strategies

In Harenna Buluk and Dello Menna districts, livelihood diversification was the most practiced strategy among homegardeners, followed by agricultural intensification. This finding is consistent with Das (2020) and Ellis (1998), who reported that rural households in developing countries are most likely to pursue livelihood diversification. In contrast, migration as a livelihood strategy was rarely observed. Traditional homegardeners tended to choose livelihood diversification due to limited access to irrigation, improved seeds, and extension services. Similar patterns are likely observed in other farming activities, where constraints force households to rely on diversification rather than intensification.

Households practicing improved HGAF, however, tended to adopt livelihood diversification and agricultural intensification equally, reflecting their greater capacity to advance and intensify farm activities. This finding aligns with Das (2020), who indicated that households with higher incomes are more likely to undertake agricultural intensification compared to economically poorer households. These results highlight the importance of improving HGAF systems through access to irrigation, improved seeds, and extension services, interventions that could also benefit other farming systems. Enhanced access and opportunities enable households to pursue agricultural intensification alongside livelihood diversification as complementary strategies.

3.5. Socioeconomic benefits of HGAF to households

Food and income were the primary socioeconomic benefits of HGAF in Harenna Buluk and Dello Menna Districts. Food and income accounts for the largest percentage of

household benefits among those who practice improved HGAF. Thus, improving the HGAF with an irrigation system and improved seed and advisory service results in a HGAF that outperforms its income. This was comparatively due to HGAF intensification through support by extension services, which has increased their income from homegardening. This finding was consistent with the findings of Baul *et al*. (2021), who reported that the HGAF contributed significantly to household income. However, food sources account for the largest portion of household benefits for households who practice traditional HGAF. Our finding for both improved and traditional HGAF ranges between reports from other countries, which report HGAF shares household benefits ranging from 20 to 60% (Mohri *et al*., 2013).

4. Conclusion and Recommendations

This study shows that livelihood diversification and agricultural intensification are the primary strategies adopted by households in Harenna Buluk and Dello Menna Districts. Households practicing improved homegarden agroforestry (HGAF) focus more on agricultural intensification, while traditional HGAF households rely mainly on livelihood diversification. HGAF significantly contributes to both food and income security, particularly for households using improved systems. However, homegardeners face multiple challenges, including pests and diseases, water scarcity, limited technical skills, inadequate capacity-building opportunities, weak market linkages, and climate change impacts. These constraints are especially severe for traditional HGAF households during dry seasons, highlighting the urgent need for irrigation systems and improved access to extension services and agricultural technologies. Additional barriers—such as poor transportation, limited market access, and wildlife damage—further restrict income growth and hinder the adoption of improved practices.

To address these challenges, the Ministry of Agriculture should develop supportive policies that encourage HGAF adoption as a sustainable income source and improve access to agricultural technologies while strengthening extension services to fill training gaps and promote best practices. Recognizing and rewarding top-performing farmers can motivate wider adoption, and strengthening market linkages and infrastructure, including rural roads and transport networks, will enhance market access and income opportunities. Collaboration among research institutions, extension agencies, agricultural organizations, and development partners is essential to facilitate knowledge sharing and peer learning, complemented by experience-sharing visits within and beyond the study area. Further research is also needed to understand factors influencing HGAF adoption, evaluate trade-offs in species composition, and assess the long-term impacts of HGAF on soil health and ecosystem services.

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Beyond Technology Transfer: How Extension Agents Drive Agricultural Innovation Systems in Northwest Ethiopia

Yemane Asmelash Gebremariam[1], Joost Dessein[2], Beneberu Assefa Wondimagegnhu[3], Mark Breusers[4], Lutgart Lenaerts[2], Enyew Adgo[5], Steven Van Passel[6], and Amaury Frankl[7]

[1]Department of Rural Development and Agricultural Extension, Bahir Dar University, Ethiopia
[2]Department of Agricultural Economics, Ghent University, Belgium
[3]Policy Studies Institute Ethiopia, Economic sectors policy studies, Ethiopia
[4]Institute for Anthropological Research in Africa, KU Leuven, Belgium
[5]Department of Natural Resource Management, Bahir Dar University, Ethiopia
[6]Department of Engineering Management, University of Antwerp, Belgium
[7]Department of Geography, Ghent University, Ghent, Belgium
*Correspondence Author: yemhaben@yahoo.com

Abstract

Rural innovation and agricultural extension take many different forms, but all rely on extension agents who have strong skills in both technology transfer and innovation systems. When extension agents are well equipped, they can effectively support the individuals and groups they serve across agricultural communities. A flexible and responsive extension system is equally important to ensure services reach farmers in a timely and meaningful way. Yet, in practice, extension agents often assume they know what farmers need, which can unintentionally limit farmers' participation and stifle local innovation. In Ethiopia, extension agents are at the center of a major shift from the long-standing technology transfer model to a more collaborative and adaptive agricultural innovation system approach. To understand this transition, the study used a qualitative design drawing on 22 key informant interviews and 23 focus group discussions with men and women in Fogera and North Mecha districts of Northwest Ethiopia. The data were analyzed using NVivo 12 through a thematic and deductive framework. The findings show that extension agents play many, and sometimes conflicting, roles. They act as facilitators, reporters, model farmer selectors, persuaders, innovators, suppliers, intermediaries between researchers and farmers, trainers, technology disseminators, and resource linkers. Although the Technology Transfer approach remains dominant, extension agents increasingly require Agricultural Innovation System oriented skills to effectively support smallholder farmers. The study emphasizes the need to strengthen the institutional capacity of agricultural organizations, so the extension system becomes more client-focused and responsive, both to the needs of smallholder farmers and to those of the extension agents themselves.

Keywords: Development agents, model farmer, extension system

1. Introduction

In Ethiopia, agricultural extension service is top-down, though the system is decentralized (Gebremariam *et al*., 2021; Farnworth *et al*., 2018; Albore, 2018; Berhane *et al*., 2018; Deneke & Gulti, 2016; Davis *et al*., 2010; Belay & Abebaw, 2004). Extension services are supply-oriented, with little regard for farmer demand or anticipation of further adoption. For instance, for model farmers[1] most extension services are provided by agricultural extension agents (EAs), who are responsible for providing them (Abegaz & Wims, 2015; Beyene, 2017; Girma & Kuma, 2021; Hailemichael & Haug, 2020). Extension agents primarily offer technical services to farmers based on organized programs and policies of the Ministry of Agriculture (MoA) for rural development.

In Ethiopia, extension agents advised more than 80% of farmers on using improved seed at a time, planting in rows, treating seed, controlling pests and diseases, promoting farmer connection with a financial institution, training on agricultural techniques, and fertilizer use (Beyene, 2017; Girma & Kuma, 2021). Ethiopia has significantly invested in agricultural extension services through these agents because of their economic and political contributions to the country. These, in turn, help the government increase agricultural production and productivity goals. With the most considerable extension agent-to-farmer ratio of any country, Ethiopia is thus regarded as a global leader in providing farmer-extension services (Figure 1).

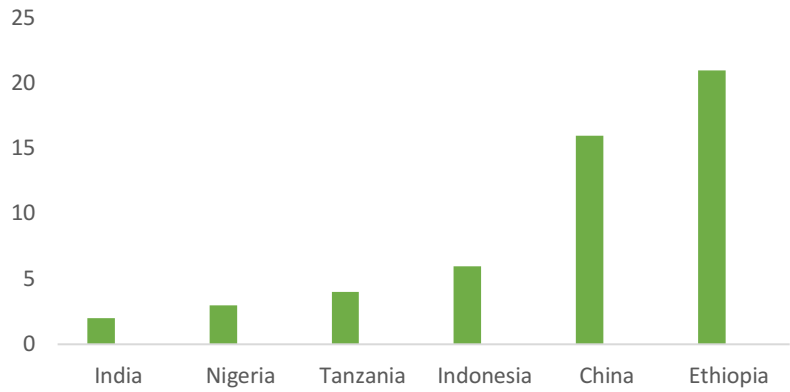

Figure 1. Number of agricultural extension agents per 10000 farmers in selected countries.

With 62,764 extension agents (EAs) trained and 45,812 reportedly employed locally, the Ethiopian district field-level extension service has a solid extension foundation (Jilito & Wedajo, 2021; Davis *et al*., 2010). This suggests that the main issue for the government is not the increasing number of agents but the need for systemic management to handle the existing human resources (Hailemichael & Haug, 2020).

[1]Local government institutions select a model farmer as a role model for neighboring households.

Despite a growing number of development agents, the advising service still needs to meet farmers' needs (Leta *et al*., 2017a). This is due to, for instance, regardless of their discipline backgrounds (either crop, livestock, or natural resource management), EAs provide comprehensive advisory services for crops, livestock, and natural resource management at the sub-district level (Berhane *et al*., 2018). As a result of a lack of practical skills from extension agents across many disciplines, the quality of consultation needs to improve and stay within expectations (Belay & Abebaw, 2004). Aside from the concerns above, agriculture personnel, in general, are the lowest-paid members of the district when compared to other sector offices.

Additionally, EAs lack job facilities and incentives such as a daily stipend or top-up, housing, transportation, insurance, or field supplies. These, in turn, lead EAs to need help to deliver effective consulting services in their field. The District Office of Agricultural Development (DOAD) is likewise distinguished by poor institutional decentralization and a lack of planning ability and decision-making authority (Snyder *et al*., 2014).

Even though Ethiopia has invested heavily in its agricultural extension system, the long-standing Technology Transfer (ToT) model is no longer meeting the changing needs of smallholder farmers or the extension agents (EAs) who support them. Extension agents are expected to navigate diverse local challenges, yet the system they work in offers limited flexibility, weak incentives, and inadequate institutional backing. Because of these limitations, EAs often struggle to perform their increasingly demanding roles, and farmers continue to receive services that are prescriptive rather than participatory or innovation-driven.

There is growing recognition that moving from the ToT model toward an Agricultural Innovation System (AIS) approach could better empower both farmers and EAs. However, there is still little understanding of how this transition is taking place on the ground. We do not yet know which roles EAs are performing, how these roles are evolving, or how their everyday realities align with the expectations of a more innovative, collaborative extension system. This lack of clarity has contributed to gaps in service delivery, low farmer engagement, and unclear accountability within the extension structure.

To build an extension system that truly supports rural innovation, it is essential to understand the context-specific responsibilities EAs carry and the challenges they face. Such evidence is also critical for informing policymakers on how to improve the working conditions, motivation, and professional growth of EAs as Ethiopia gradually shifts toward an AIS-oriented approach.

Against this backdrop, the study seeks to answer the central research question: What are the actual roles and responsibilities of extension agents in information and

knowledge dissemination within local extension systems that are transitioning from a Technology Transfer (ToT) model to an Agricultural Innovation System (AIS) approach?

2. Materials and Methods

This research was conducted in two districts around Lake Tana in northwest Ethiopia. Mecha district is found administratively in the West Gojjam Zone of the Amhara Regional State. Mecha is known for its irrigation potential and is the home of the multinational vegetable brand Koga Veg (a Belgian-based company that exports fresh fruits and vegetables). Fogera district is situated in Ethiopia's Amhara regional state's South Gondar zone. The Fogera district is widely recognized for producing rain-fed rice and irrigated vegetables. In both districts a variety of public extension agencies operating in the area provide extension services in the two districts (Gebremariam *et al*., 2021).

The study used qualitative research design, and a qualitative approach was deployed to analyze the data generated. Next, content analysis using an inductive technique (Bernard 2006) was carried out in the NVIVO Qualitative Data Analysis Software QSR International (2020) to create themes based on the data to gain insight into the roles of extension agents and the enabling environment. Finally, twenty-three Focus Group Discussions (FGDs) with men and women farmers were conducted. Each FGD had seven to nine participants and lasted one and a half hours. Discussions were held in Amharic and audio recorded. 22 Key Informant Interviews (KIIs) were conducted with staff members of agricultural offices at different levels (Table 1). Specific topic lists were used to contextualize each interview for each type of actor. The interviews were also audio-recorded.

Table 1. Data collection at the implementation level

Key Informant Interview (KII)	Level	Type of actors	Number of interviews
Extension agents	Sub-districts	Plant, animal, and NRM extension experts	10
Bureau of Agriculture	Region	Extension expert	1
Research Institute	Region	Socio-economics researcher	1
The district office of Agriculture	Districts	Extension process owner Extension monitoring and evaluation expert	2 1
Fogera rice research and training center	National	Center director Agricultural economics and extension unit coordinator	1 1
Workshop with agriculture experts & and farmers	District and sub-district	Extension process owners, extension monitoring and evaluation experts, plant, animal,	4

ATVET	Region	and natural resource experts, farmers Extension Instructors	1
Total key informant interview			22
Focus group discussions (FGDs)			
Farmers	District		23
Total KII & FGD			45

Observations in Kebelles[2] and informal discussions provided additional insights. Participant observation during farmers' field days allowed for the study of extension agents' interactions with farmers, focusing on their two-way communication.

The first author translated, transcribed, and coded the KIIs and the FGDs using NVivo, version 12, to allow a thematic, deductive approach (Brandão, 2015). First, inductive coding was done after reading each transcript line by line, generating a list of codes, and designing a system of categories. Next, triangulation was done by including information from observations made in the field. The resulting node tree and code structure allowed selective coding (Dhakal, 2022).

3. Results and Discussion

Farmers' primary sources of information are sub-district EAs. EAs exchange information about row sowing, pesticides, markets, artificial insemination, illnesses, pests, and other aspects of agriculture. EAs also introduce some fresh farming innovations. During input distribution and training at the farmers training centers (FTC) level, farmers interact with the extension agents. Additionally, farmers request guidance from the EA office on where to find inputs for their harvest. Based on the findings, farmers rated the information source from extension agents as very strong (61.67%) in the district (Table 2).

Table 2. Level of farmers' interaction with extension agents

Interaction of farmers for information need with EAs	Freq.	Percent
Very weak	13	4.33
Weak	26	8.67
Strong	76	25.33
Very strong	185	61.67
Total	300	

During the course meetings and workshops, EA also teaches farmers about the benefits and drawbacks of taking out a loan. However, they are not mandated to be involved in

[2] The smallest administrative units in Ethiopia

credit repayment activities. One of the extension agents from Fogera said, *"EAs facilitate agricultural credit from financial institutions. He added that they link farmers with sources of farming inputs and credit facilities, which are ACSI (Amhara Credit and Saving Institution) and sometimes multipurpose cooperatives located in the sub-district*." (Sub-district extension agent, KII, May 23, 2019).

The Knowledge level of extension agents is theoretically sound, but they are less expected to be practical. Extension agents are responsible for regularly spreading technology to the agricultural community. Their work capacities determine their capacity to do extension tasks.

"I excel in theoretical aspects of crop production and protection" (Sub-district extension agent, KII, May 23, 2019). *"But I may be alleged to be weak at showing farmers practical,"* one extension agent stated (Sub-district extension agent, KII, May 23, 2019). The extension agent said that this resulted from the ATVET course delivery method, which, although stating that it is 70% practical and 30% theoretical, has not been applied. A farmer responded in a group discussion that there are extension agents who cannot discern between Wheat and Barley at the seedling level.

The extension process owner for the Mecha district stated, "*In fact, the ATVETs did not provide extension agents with the requisite practical skills."* (District process owner, KII, June 5, 2019) {Grossi, 2023 #2}. He explained that the district compensates for shortfalls by providing practical focus training.

Extension agents were expected to induce the party's political ideology and enable farmers for election purposes. An extension agent confirmed she was chairing party conferences and meetings during election seasons. In their regular extension work, it was observed that some extension agents focused on political matters in addition to development activities. According to the Fogera district extension process owner, extension agents are expected to serve in both political and development roles. One extension agent from Fogera strongly opposes this and said, *'My responsibilities as an EA include providing skill training to farmers, visiting farmers' fields, facilitating farmers' access to agricultural inputs, demonstrating the technology, and gathering information about farmers' needs to plan input requirements.'*. (Sub-district extension agent, KII, May 23, 2019). Another extension agent from Mecha district highlighted the issue, *''I was required to become a member of the ruling party and to carry out party-related responsibilities. As a result, my performance was assessed based on the extent to which I fulfilled those duties.''* (Sub-district extension agent, KII, May 23, 2019).

On the other hand, some extension agents become members of the ruling party to access opportunities such as training, further education, and promotion. Similarly, graduates seeking employment after college may also join. The overlap between political involvement, knowledge, and professional skills creates challenges for extension work in both districts. For example, a farmer from Fogera stated: “I do not

want to listen to the lectures of those 'model farmers' who act like political representatives; they are misleading themselves and me. I am more capable than they are, even in farming activities." (Farmer, FGD, July 12, 2019). According to extension agents, farmers are not forced to do things by EAs. On the contrary, EAs make every effort to persuade them. Nevertheless, some extension agents feel farmers' behavior may be coercively or willingly changed. For example, farmers stated during group discussions that the EAs coerced them to attend meetings and closely check their availability. In addition, EAs described that farmers are demanding to persuade since they rely on conventional farming methods. However, farmers recalled how EAs had previously persuaded them to use fertilizers by testing the fertilizer to demonstrate and convince them that it did not contain a poisonous substance and would not hurt the crop.

An extension agent from the Mecha district said that '*post-harvest was the biggest problem reported in my domain location, and I am aware of the requirements and concerns of farmers. Therefore, during field days and training sessions, many farmers accepted and reinforced my recommendation to use plastic (hermetic) bags.*' (Sub-district extension agent, KII, May 12, 2019).

Two farmers in the FGD gave their witnesses their views on its efficiency of chemicals. A farmer's testimony from Fogera district is: *' I tested the chemical on my farm in a 10 x 20-meter plot, and it works well. Moreover, the EA also informed me that it is less expensive than the chemical I purchased from a store.'* (Farmer, FGD, June 12, 2019). The second farmer from the Fogera district added: *' It was my first time witnessing such ingenuity from our agricultural helper at a time when numerous strangers were visiting our sub-district and attempting to persuade us to use specific technology. This chemical appeals to me since it is free. Moreover, it successfully lowers the bug population on my land.'* (Farmer, KII, June 12, 2019).

The EA explained that he prepared organic pesticides to control 'Guya'' (Grass pea (*Lathyrus sativus)*, which is the most widely cultivated crop in the study area. However, it has yet to be scaled up. He continued by saying that the Fogera district and the south Gondar zone had recognized his ingenuity. The Fogera Rice Research Center in the district has investigated the chemical scientifically but has not yet approved or disapproved of it. He added that the compound is environmentally friendly and not harmful to humans. It is made up of ginger, garlic, and motor oil. Therefore, farmers can easily prepare the chemicals at a low cost.

This distribution method of Input/fertilizer has been changed, and the current scenario is as follows: Fertilized distribution is determined by the size of the land to be cultivated and the type of package used by farmers. The size of the area that will be farmed and the type of package will be used by the extension agent to determine each farmer's needs. Farmers go to the cooperatives, pay Amhara Credit and Saving Institution (ACSI) money, and then return the receipts. Farmers get fertilizer right off the bat.

Extension agents were conducting meetings with farmers and other stakeholders in the research area. They never, however, evaluated the outcomes of the sessions. Furthermore, extension agents provided training to farmers without first doing training need assessment (TNA), and even after that, they still needed to assess the benefits or downsides of training. Most training was organized for those farmers who were better-off and politically affiliated. However, an EA argued that his stand or decision was that farmers who are sent to training and do not put their training into practice would not be given another chance to train.

Manipulated and exaggerated reports are common phenomena in the districts. Both district extension process owners stated that the number of farmers participating in extension programs was substantially inflated; the amount of output per hectare for specific commodities was exaggerated. Additionally, extension agents produced inflated data on plantation coverage exceeding their sub-districts of land. For example, an extension agent from Fogera said, *"One of the current constraints on the efficacy of agricultural extension services is the reporting system. I was directed by the head of the district office of Agricultural Development to process and create fabricated and exaggerated reports."* (Sub-district extension agent, KII, May 12, 2019).

The finding showed that the extension system changes from the transfer of technology (ToT) to a more "enabling" environment for extension agents. Extension agents are considered teachers of farmers, and they are, in general, called adult instructors. Extension agents instruct farmers at FTCs and farmers' fields. Nevertheless, farmers suggest providing extension services and promoting agricultural technologies through the farmer-to-farmer approach. Khaila *et al*. (2015) assert that farmers learn best from their peers, and their groups or communities in Malawi select about 75 percent of lead farmers.

Ethiopia's extension agents' capacity-building schemes focus on theoretical and technical skills. Therefore, the absence of "soft" skills in the ATVET curriculum, such as group development, communication, facilitation, and entrepreneurship, leads to less support for smallholder farmers and urges capacity-building needs of extension agents for effective communication. Therefore, the Ethiopian Ministry of Agriculture and its organizational structure emphasize the importance of extension agents' soft skills throughout training sessions, workshops, and conferences. However, because it is not included in the long-term capacity-building programs, extension agents are prevented from primarily playing the facilitation function and carrying out their duties as technology disseminators. For instance, according to a recent study on Ethiopia by Yitayew *et al*. (2021), the use of herbicides and pesticides is significantly impacted by the introduction of the new wheat variety to the EAs and the provision of training on soft skills for process facilitation and effective communication made up of technology innovation communication and participatory extension methods.

Farmers need better technology, and extension agents are responsible for disseminating it. A considerable investment in agricultural extension services is making training available to farmers to improve their practices, knowledge, and skills. Therefore, understanding the training needs of the farming community is essential to providing farmers with appropriate training. Training Need Assessment (TNA) targets the following circumstances: finding and fixing the specific issue; avoiding repeat, which saves time and money; determining what the potential future issue might be and acting; and providing learning, development, or progress. However, extension agents should have considered the farmers' interests when choosing topics, designing the curriculum, or developing it. This was consistent with what had been discovered, which demonstrated that extension agents provided training and capacity-building programs to farmers without conducting TNA using a general curriculum and without considering differences in the socio-economic characteristics of the extension service's end users (Wallenborn, 2009).

Farmers desire better technology and have sought advice from extension agents. However, with poor research-extension linkage, extension agents' innovation ability is limited. Financial constraints, a lack of collaboration and communication with technology developers, and sporadically, the availability of uninspiring extension agents by innovations may all contribute to these. Our findings broadly concurred with Muzari *et al*. (2012). They claim that extension agents are only tangentially connected to research and continue repeatedly communicating the same messages to the same audience. They state as much in their review of how technology adoption impacts smallholder agricultural productivity in sub-Saharan Africa.

One aspect that may influence the adoption of agricultural technologies is farmers' financial capacity. Saving money is one way for farm families to meet their needs when they are not productive or during a critical period. Avoiding superfluous expenses for social occasions leads to poverty. Extension specialists have provided guidance and instruction on how farmers might save money to enhance their quality of life. This finding is comparable to Hundie *et al*. (2004). They reported that extension agents were hired to help farmers avoid unforeseen costs associated with formal social events, including weddings, funerals, engagement parties, and circumcisions. Since agricultural credit was included in the extension services that farmers required, extension agents assisted farmers in setting up financial organizations, which could be formal or informal, strengthening Equb and Iddir and encouraging them to take part in local development initiatives. Extension agents also recommended that farmers take credit from nearby financial institutions, like ACSI, to help them overcome their financial shortage when purchasing farm inputs. This finding agrees with Moahid *et al*. (2021), who also found that creating awareness of formal credit impacts farmers in rural areas of Afghanistan.

Government priorities place significant pressure on the daily work of extension agents. For example, performance evaluations are based on the quantity of fertilizer and

improved seeds distributed by EAS staff and the number of farmers encouraged to participate in related programs. Furthermore, the information provided in the district office of agriculture's efficiency format, which had to be completed every six months, needed to reflect how extension agents performed their job descriptions. According to Mazwi *et al*. (2019), regarding the political motivations of the public extension services, Zimbabwean public extension service providers could not hire extension agents based on qualifications rather than politics. Berhanu and Poulton (2014) have documented similar findings regarding the investment in agricultural extension as a second objective and understand the political significance of agriculture within Ethiopia to contribute to securing political control across Ethiopia's large and diverse countryside. As a result, making agricultural extension demand-driven remains difficult in Ethiopia. Party affiliation has provided the proper emphasis for both EAs and model farmers. Model farmers were chosen based on their political positions, as evaluated by community members in the region and the sub-district manager, for example, in Bangladesh (Faruk & Maharjan, 2022). Extension communications were only partially free of political aims, and farmers perceived extension personnel as government representatives rather than development workers (Belay, 2002).

An extension agent has engaged in community outreach efforts to hasten the adoption of innovations. Extension agents are motivated and initiated to solve farmers' problems. Extension agents identify and prioritize to address farm household needs through various technologies typically delivered through direct demonstrations. In this study, extension agents take the initiative to reduce post-harvest losses and persuade farmers to adopt and employ the technology reasonably. Ethiopian farmers use hermetic bags because it has been demonstrated that they can reduce storage losses and because extension agents promote their usage. Consequently, agricultural extension agents are more enthusiastic about encouraging farmers to embrace technology-based solutions to their problems. Similarly, the authors of Ndegwa *et al*. (2016) revealed that hermetic bags are the most widely disseminated among smallholder farmers in Kenya.

The provision of essential farm inputs is boreoarctic and time-consuming in Ethiopia. Nyssen *et al*. (2017) cited in Kraaijvanger (2014) point to extension workers whose involvement in agricultural input supply is mandatory since they are closest to the grassroots level. Moreover, unavailability and late delivery of farm inputs were the main constraints farmers and extension agents faced in achieving the desired objectives. However, extension agents in the study area streamline the service process by cutting down on the administrative layer. Farmers, as a result, receive prompt input delivery services. In addition, extension agents provide farmers with the knowledge to apply fertilizer and voluntarily assist with input delivery systems to speed up the lengthy process. The finding confirms earlier studies in rural Ethiopia's geography of public service delivery (Abate *et al*., 2020).

The district extension process owner must receive reports from extension agents on their activity. One of the barriers to the efficacy of agricultural extension services is the reporting system. This result was supported by Leta *et al*. (2017b), who indicated that the district extension process owner often imposes pressure on EAs and produces exaggerated and logically unreliable reports. Hence, the performance evaluations of EAs may suffer if they refuse to follow the extension process owner's instructions. Matouš *et al*. (2013) also showed that extension agencies at different levels in Ethiopia greatly overestimated the amount of training farmers received. As a result, data was altered by these public agencies to exaggerate success and boost performance ratings. Senior-level managers are the only ones who decide what regular extension tasks EAs will take on. The poor incentive and reward structures that define governmental extension services in developing countries are significant drawbacks.

4. Conclusion and Recommendations

The findings show that extension agents take on a wide variety of roles, some of which overlap and occasionally even contradict one another. In their everyday work, they guide farmers through new practices as facilitators, compile and send information to higher-level offices as reporters and select model farmers within their communities. They also work as persuaders who promote certain technologies, suppliers who provide essential inputs, and, but not as innovators who try out new ideas. Beyond this, they serve as intermediaries linking researchers with farming communities, as trainers who build farmers' skills, as disseminators of agricultural technologies, and as resource linkers who help farmers connect to needed services.

Even with this broad and demanding set of responsibilities, the Technology Transfer (ToT) approach still shapes much of how extension work is carried out. Yet, as farming becomes increasingly complex and context-specific, extension agents need stronger Agricultural Innovation System (AIS) skills such as collaboration, problem-solving, knowledge sharing, and supporting farmer-led innovation. These capacities are essential if extension agents are to effectively help smallholder farmers navigate today's changing agricultural landscape.

For AIS to truly take hold, the study highlights the need to build stronger institutional support within agricultural organizations. Strengthening these institutions would allow the extension system to become more client-centered and responsive to the needs of both farmers and the agents who serve them. Such a transformation is vital for creating an environment where innovation can grow and where extension services genuinely contribute to rural development.

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The Contributions of Agricultural One Stop Shops in Improving Smallholder Framers' Input Access in Ethiopia

Asamenew Shimeles*, Simachew Mekonnen, Dagnachew Lule, Yitbarek Semeane, Weyessa Garedew, Mulu Assefa, Zerihun Misgana, Yaregal Agidew, Haileyesus Abate, Girma Zeleke, Dereje Tolesa, Degefa Negassa, Bekele Damte, Diriba Fufa, Manyazhal Shegaw, Lemlemneh Zekarias, Abiot Mekonnen, Yedemie Yeshalem, Abiyot Endalew, Fisehatsion Kebede, Tesfaye Tadesse, Berihu Kidanu, Tesfay Kiros and Yeshiwas Assefa

Agricultural Commercialization Clusters (ACC) Programme, Ethiopian Agricultural Transformation Institute (ATI), P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding author: Email: asamenew.shimeles@ati.gov.et

Abstract

The use of agricultural input is fundamental in increasing productivity, smallholders' income, and ensuring food security. Despite the potential, agricultural productivity in Ethiopia has been low and overwhelmingly of a subsistence nature due to limited use of inputs and weak engagement of the private sector. To improve the input availability to smallholder farmers in proximity, at the right time and at the right price, the Ethiopian Agricultural Transformation Institute has designed and implemented the Agricultural One Stop Shop (AOSS) project together with diverse stakeholders at federal and regional levels. The project employed both the sub-granting and self-financing implementation modalities. A total of 348 AOSS were engaged in the process between 2019 and 2024 across the country from the Oromia, Amhara, Tigray, and SNNP regions. On average, AOSS shared nearly 86% of the cost for business operation. Reports show that the number of smallholder farmers who accessed agricultural inputs through AOSS increased from 864,738 in 2012 to 2,566,548 in 2016. The innovation systematically, but gradually, changed the agricultural input supply in the rural community, transforming it from poor sanitary and unprofessional input supply practice to a well-organized channel, professionally led business, and accountability. The AOSS project has provided a private sector-driven sustainable solution for improved access and utilization of agricultural inputs through a one-stop window. The innovation should be scaled up in areas where there are limited or no input suppliers to address the demand.

Keywords: Agricultural inputs and services, input distribution, input supply, productivity

1. Introduction

Improving agricultural productivity is one of the top priority agendas in Ethiopia to feed the country's growing population, to provide raw materials for industries and to earn income through export. The agriculture sector is expected to contribute to poverty reduction as nearly more than two-thirds of the population are directly involved in the agricultural sector. Agriculture also has immense potential for the nation's wellbeing because of vast areas of fertile land, favorable natural conditions, and large labour

pools. However, production and productivity of the agricultural sector is low due to various factors, including the limited use of agricultural inputs (IFAD, 2023). The use of agricultural inputs is fundamental in modern agriculture and farm activities. It plays vital roles in increasing SHFs' income and ensures food security. Agricultural input includes certified seed improved plant varieties, fertilizers, agrochemicals, and farm tools.

Smallholder farmers (SHFs) face numerous challenges in accessing agricultural inputs and services. Inflated input costs, inferior quality, weak private sector engagement and widespread illegal input market are the common factors, which significantly hinder agricultural growth. The input distribution system is complex, lengthy and has been challenged by poor services. Studies show that Ethiopia is one of the least performing countries in terms of utilization of agricultural inputs. SHFs often travel long distances to access inputs due to absence of service in their vicinity including key constraint of household 44Km from the road (FAO, 2018). To this end, developing an efficient input market system is crucial in ensuring SHFs access high quality input along with appropriate services at the right time at an affordable price. Moreover, removing input related constraints is critical to improve input availability, which ensures higher productivity.

In the 2010s, the Ethiopian Agricultural Transformation (ATI) and its partners launched targeted interventions to address critical gaps in the agricultural input supply and service. Strategic projects, such as Direct Seed Marketing (DSM), Direct Input Marketing (DIM) and Commercial Farm Service Project (CFSP), were specifically designed by ATI to resolve the systemic supply chain constraints. Drawing on lessons from prior initiatives and the evolving dynamics of the market, ATI launched the Agricultural One Stop Shop (AOSS) project. The initiative aimed to establish a quick and enhanced system of agricultural inputs and services and scale the retail network model originally piloted under the CFSCP (Final Evaluation, CFSP, 2018). Geographically, the project was implemented in main agricultural regions: Oromia, Amhara, Tigray, Sidama, the Southwest, Central and South Ethiopia regions.

The project was initially designed to operate at two levels – hubs, and spokes. Later, a scale up design was proposed to achieve centers and shops (like "spokes"). The project introduced participatory implementation approach through enhancing strong engagement of stakeholders with defined mandates, roles and responsibilities. This paper aims to present the contributions of the AOSS in supporting farmers to access agricultural inputs, the challenges during project implementation and lessons learned. Moreover, it describes key areas that need to be considered in further improving inputs access to SHFs. (AOSS Design Document 2018; Project Management Plan, 2020)

2. Material and Methods

2.1. Implementation sites

Initially piloted in 20 woredas across six regions, the AOSS project expanded to 311 woredas - 300 ACC woredas and 11 Integrated Shallow Ground -Water Irrigation Development Project (ISGWIDP) areas located in seven main agricultural regions. These include: Oromia, Amhara, Tigray, Sidama, the Southwest, Central and South Ethiopia regions.

2.2. The model and implementation approach

The AOSS project was strategically aligned with national agricultural policies, specifically focusing on private sector participation to resolve systemic input supply and service delivery constraints. Implementation of the AOSS model relied on the involvement of diverse groups of participants in target areas. Accordingly, the model engaged private entrepreneurs, cooperatives and community-based organizations that demonstrate the financial and operational capacity to implement the model. In line with this, the project selected potential operators for their capacity to mobilize matching funds and execute the model.

While the ATI facilitates market linkages between established centers/shops and input suppliers, governance has been managed through a structured hierarchy involving National and Regional Oversite Committee, and Woreda Technical Group. These bodies were instrumental in creating an enabling environment for AOSS business operators especially during the initial and vital stage of the project. Therefore, these partners played a critical role in successful establishment and operationalization of the outlets through sub-grant and self-finance implementation modalities as discussed in the following in the following sections.

2.2.1. Sub-grant implementation modality

As part of creating opportunities for the private sector and introducing the model, the project has been implemented with a sub-grant modality and matching fund arrangements. The rationale behind the sub-grant modality was to provide incentives and risk sharing opportunities for the private sector to leverage investments to engage in the business. Private actors were responsible for the construction of the AOSS buildings as per agreed floor standards and regulatory requirements to supply legally registered and traceable agricultural inputs. ATI's financial contribution is earmarked for key staffing, furnishing with standard operational facilities, and branding. Moreover, the support from ATI focused on supporting AOSS in staffing of three key technical personnel to enhance the professional service provision, training, and farm demonstrations.

Targeting potential business owners started with sensitization workshops, followed by collection of expressions of interest and applications. The opportunity was open to all

potential business entities, including entrepreneurs, cooperative unions, and community-based organizations. Several platforms were facilitated, including familiarization workshops, one-to-one discussions, and onsite promotion to identify the appropriate target groups. Potential business owners who fulfilled the mandatory criteria and passed the technical evaluation requirements were selected using a clear and transparent beneficiary targeting process. Experience in agricultural business and financial capability were, among others, the key selection criteria used to identify potential businesses. The selection was conducted in collaboration with woreda administrators and heads of agricultural offices.

To ensure institutional sustainability, the project developed the AOSS operational manual to maintain service standards as per the AOSS model. The manual contains key elements of AOSS establishment including the design of the building, furnishing requirements, organizational structure, and job descriptions, staffing, input stocking and management, environmental compliance, and social responsibilities. AOSS centers have an organizational structure to determine the hierarchical flow of operations and activities to deliver products and services to SHFs. Based on the redesigned model, owners have been encouraged to source input from national suppliers and wholesalers while some key input channeled through public entities were sourced through coordinated mechanisms.

2.2.2. Self-finance implementation modality

The project's sustainability concept envisioned entrepreneurs replicating the existing retail model with self-financed business and entering a competitive input marketing system. In this regard, ATI facilitated the successful transition of AOSS establishments with self-finance modality through developing technical implementation guidelines and technical backstopping. Such arrangement enabled the adoption of the AOSS model, enhancing business expansion and delivering better service for farmers. The implementation guideline was developed aligning with the MoA's directive Agricultural One Stop Shop Certificate of Competence (CoC) Licensing (2019).

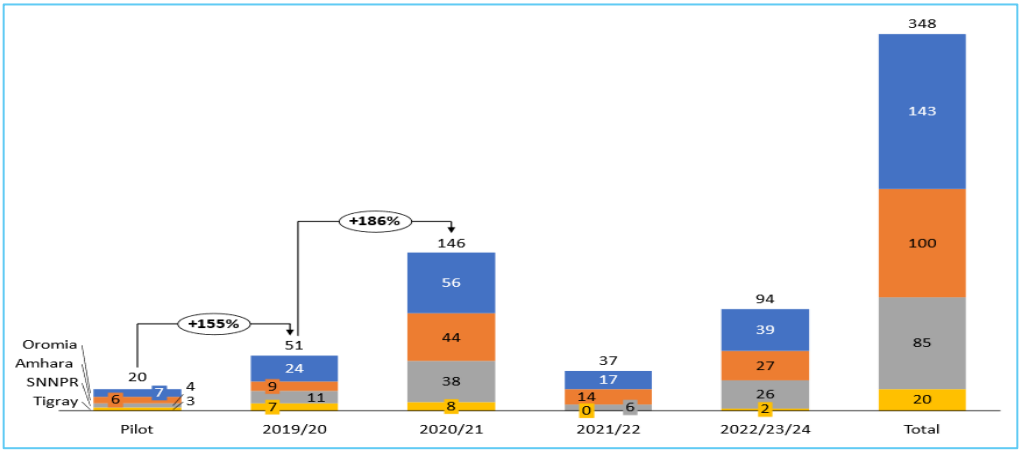
2.3. Data collection and analysis

The data were gathered from secondary sources, including project documents, baseline reports, businesses' financial reports, and project evaluation reports. The data collected considering the output matrices to gather information about the number of AOSS, training participants, and total grant disburse. Concerning the outcome matrices, volume of input sell, input sales in ETB, number of farmers served, and the trend adoption rate through AOSSs outlets were used. Descriptive analysis was adopted to analyze the data gathered. The results were presented using tables and figures.

3. Results and Discussion

3.1. Input market system establishment

The success of the AOSS system relies on a foundation of innovative solutions, rigorous technical support, implementation processes and field level support. By adopting participatory processes and integrated regional governance, the project ensured long-term local ownership. As illustrated in Figure 1, the project established 348 AOSS outlets across the main agricultural regions between 2019 and 2024. The growth peaked in 2020/21, with regional distributions including 143 centers in Oromia, 100 in Amhara, 20 in Tigray and 85 across the former SNNP region.

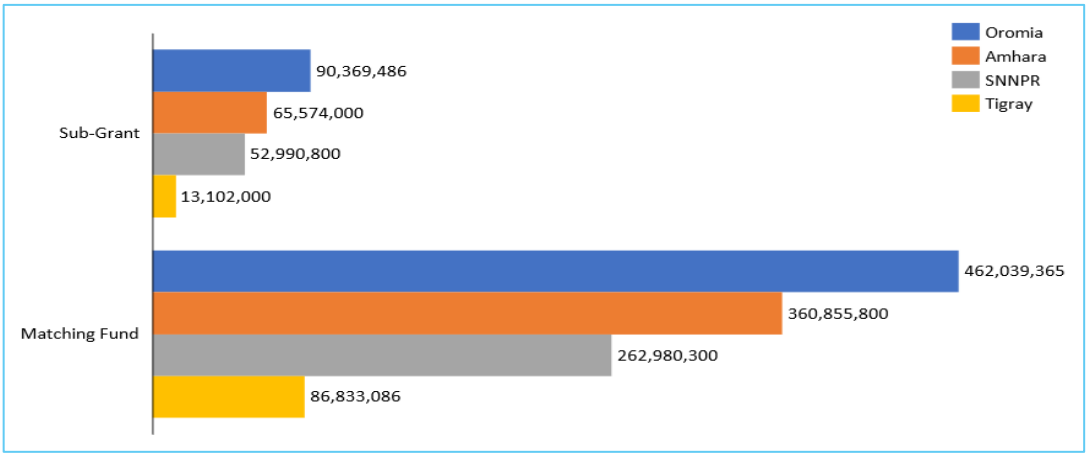


Source: AOSSP Terminal Report (2024)

Figure 1. Input market system establishment by regions over years

3.2. Private sector engagement

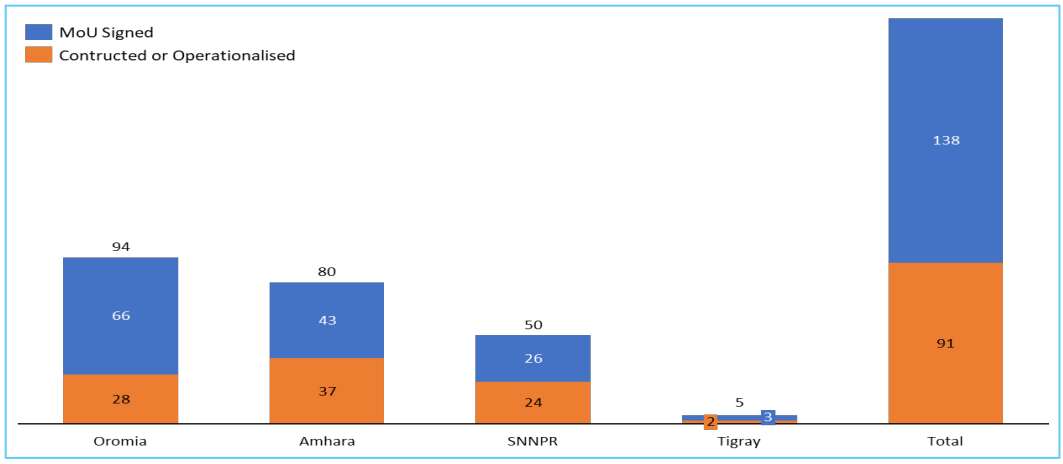
To stimulate private sector investment in the agricultural input business, the ATI utilized a sub-grant model as part of incentivizing their participation and offering risk-sharing opportunities with the private investors. The strategy successfully leveraged significant private capital, contributing an average 86% of the total required to establish and operate the AOSS system, with a minimum contribution of 70%. This implies a significant proportion of the matching funds have been shared by the private sector. A total of ETB 1,172,702,551 was invested as matching fund by 234 AOSS and nearly ETB 222,036, 286 as subgrant fund by ATI (Fig 2).



Source: Authors' compilation using Sub-Grant Agreement Document and project performance data

Figure 2. Matching Fund Contribution.

A significant milestone was the project's transition to a self-financing modality with 138 entrepreneurs entered into AOSSs establishment committing an estimated ETB 690 million to establish new AOSS outlets. Hese outlets function as collaborative system entities partnering with local government offices to perform market/input demand assessments, farmers training and field demonstrations. Figure 3 illustrates the growth of self-finance AOSSs.

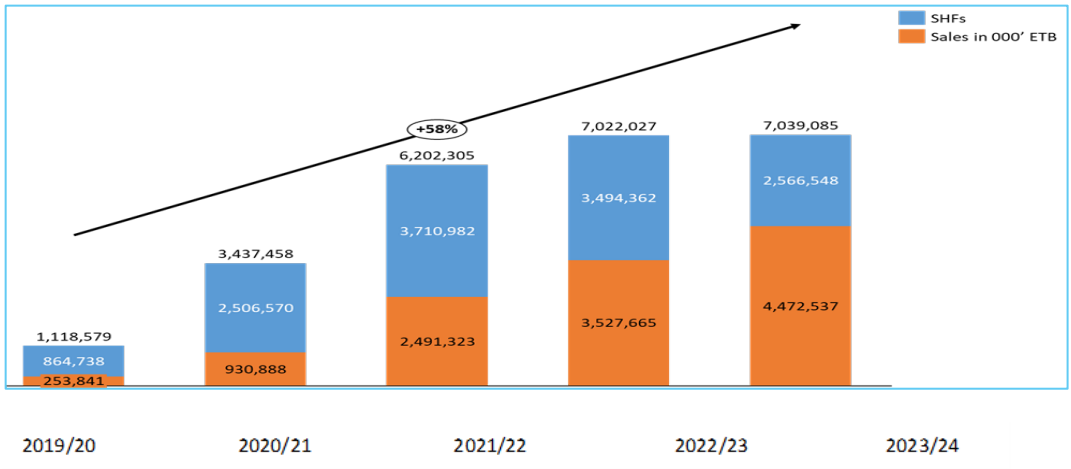


Source: Project monitoring data
Figure 3. Establishment status of self-finance AOSSs

Figure 4. Sample AOSS center's construction and distribution map

3.3. Access to input and services

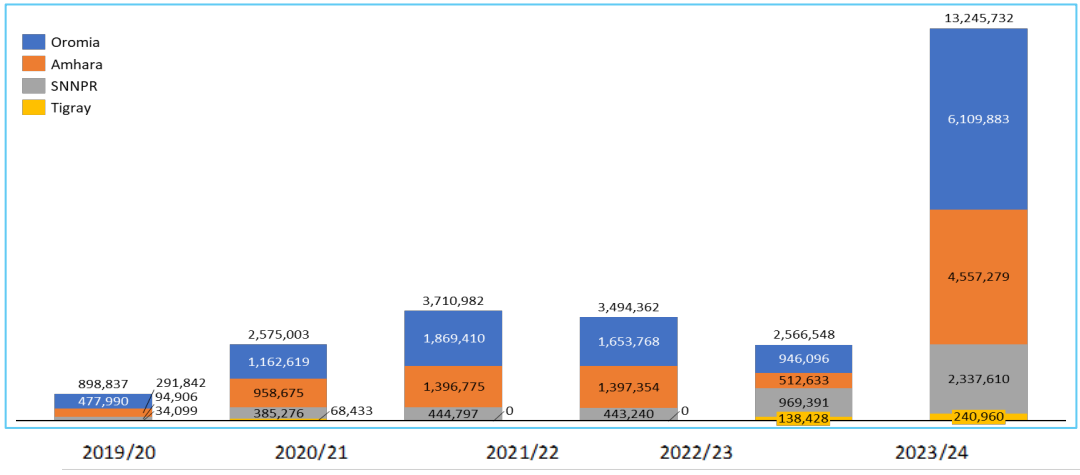
Fulfilling the project's goal of creating a consistent and quick path to an enhanced system of supply of agricultural inputs and services to SHFs, the AOSSP scaled its impact to include 13 million farmers' transactions (nearly 20% women) significantly enhancing service delivery for SHFs. In line with this, the network facilitated total transactions worth ETB 11 billion. A key factor in this success is the 'One Stop' concept that contributed to the transition of outlets into comprehensive service center that offer inputs, services and technical advisory alongside the inputs retail business. Figure 5 below illustrates the increased SHFs' transactions during the project implementation period.



Source: AOSSP Terminal Report 2024

Figure 5. Transactions through AOSS outlets

Furthermore, based on the mid-term evaluation, the percentage of households using improved seeds increased to 45 % from 63% in the project intervention woredas (AOSS Mid-term Evaluation Report 2021, FSC Baseline Report 2017). Results showed that AOSS has performed better in providing the required quantity of inputs within an acceptable time limit. As illustrated on Fig 6 below, Oromia (6 million) and Amhara (4.6 million) saw the highest engagements. Furthermore, established outlets continued to provide SHFs with agronomic support, animal husbandry, and advisory services in addition to the traditional retailing practice in the agricultural input business.



Source*:* Project *Monitoring Data*

Figure 6. Improved Access to Inputs - by the Region and Number of SHFs

3.4. Contributions of the system

The strength of the model lies in its scalability, replicability, and alignment with the community needs. As an innovative intervention, the project provided a centralized input supply and service delivery outlet thereby contributing to product quality. Furthermore, the model directly supports national policies aimed at enhancing rural livelihoods and farmers productivity. Its primary differentiator is the 'One-Stop-approach, which integrates all inputs (crop, livestock/veterinary drugs, improved seeds, farm tools, etc.) distribution with technical advisory service.

By fostering a competitive market environment, the AOSS model accelerates the commercialization of smallholder agriculture and increases the adoption of modern agricultural inputs and technologies. The innovation systematically, but gradually, changed the agricultural input supply in the rural community transforming it from poor sanitary and unprofessional input supply practice to a well-organized channel, professionally led business, and accountability (Figure 7).

Figure 7. Shifting practices in input supply

Furthermore, the evaluation results revealed that the AOSS intervention has contributed to increased income apart from transformation of the input business. More specifically, based on the assessment results, SHFs' income has almost doubled from its baseline values in target areas (AOSS Mid-term Evaluation Report 2021). By enabling improved access to input and servicing, the project proved to be highly relevant in addressing the needs of SHFs improved access to inputs thereby contributing to increasing production and productivity, income, and market linkages.

Beyond agricultural productivity, the project has significantly increased local employment opportunities by creating demand for skilled personnel to manage or operate AOSS outlets. Towards this end, the AOSS initiative has successfully generated 3,224 direct jobs, providing qualified professionals with opportunities in local outlets operations and management. By integrating an inclusive recruitment mechanism, the project specifically encouraged women participation through a 5% incentive for women ownership in the technical evaluation scoring. This strategy ensured the project not only addressed the farmers ne but also promoted the importance of

women engagement in the inputs supply and service delivery within the agricultural sector.

3.5. Sustainability

The project's sustainability strategy was built on the premise that financial viability would drive expansion through private entrepreneurs. To this end, financial sustainability has been the primary engine for the model expansion with outlets through efficient networking with bulk suppliers. The strong linkage with bulk suppliers (wholesalers) and supporting the establishments of regional apex companies enabled quick and efficient input sourcing. Smallholder farmers favor the AOSS model for its reduced bureaucracy and superior delivery speeds.

The model's long-term viability has been further secured by the MoA 'integrated input approach and endorsement of related directives that have embedded AOSS into regional governance structures. This combination of profitability and institutional alignment has created as self-sustaining ecosystem that contributes to attract private investment independently of external funding. As a result, the institutional fit model has successfully catalyzed the involvement of self-financing AOSS entrepreneurs within the ACC woredas.

4. Conclusion and Recommendations

The use of agricultural input is fundamental in increasing agricultural production, productivity and improving smallholders' income and ensuring food security. To this end, the AOSS project has successfully introduced a sustainable, private-sector-led model that centralized inputs, services and technical advisory service through innovative 'One Stop' window. By utilizing an objective, transparent selection process for potential entrepreneurs and maintaining strong stakeholders' engagement, the project ensured local buy-in and alignment with the national agricultural priorities, strategy and policy. The MoA, that bears the central responsibility for registration and licensing of AOSSs, further institutionalized the AOSS model by endorsing two legal directive (one pilot) for AOSS operators while the ATI's linkage and coordination role effectively socialized the model across all levels of government.

While the established systems have been serving the farming communities, there were certain issues that persist and impact on the affordability and quality of agricultural inputs and services. The private AOSS operators still face restrictive access to essential inputs such as fertilizer and improved seeds that are mainly controlled by public entities. They also encountered challenges associated with widespread illegal input trading mainly at the lower level of the government structure due to limited inspection and control systems. To address the challenges, the ATI has initiated national consultative platforms during the project period. Ultimately, the AOSS model has proven its resilience, maintain service even during security and supply challenges.

Smallholder farmers priority for quality, transparency, and flexibility of private AOSS outlets signals a clear demand for the model to be scaled to Las Mile Input Supply and Service Delivery to eliminate remaining distributions gaps.

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Transforming Ethiopia's Agricultural Research System through Commercialization

Melese Mulugeta* and Reta Wagary

Ethiopian Agricultural Transformation Institute (ATI), P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding Author: Melese.Mulugeta@ati.gov.et

Abstract

The Ethiopian agricultural research system contributes to the development of the national economy through technology generation, promotion, capacity building, and advisory service. However, the system cannot improve its contribution due to financial limitations, as the funds are mainly from government sources. To address the challenge, the Ethiopian Agricultural and Rural Development policy strongly recommends commercialization of the agriculture research system in Ethiopia to contribute to the agriculture sector. The present study was carried out with the objective of providing context-specific recommendations for the successful commercialization of Ethiopia's agricultural research system. The study employed desk review, key informant interview, case studies, and international benchmarking. The findings confirm that the Ethiopian research system possesses untapped potential that could be turned into growth factors and transformation through commercializing research outputs and related services. The research system could also consider alternative funding sources to reduce the burden on public funding and ensure sustainability. Furthermore, the policymakers should support the research system to directly use the revenue collected for research activities.

Keywords: Financial limitations, Rural Development policy, Technology generation

1. Introduction

Ethiopia's public agricultural research experience has a history of more than 55 years and its present organizational arrangements evolved over time. The Ethiopian agricultural research system has served as a main driving force for agricultural growth by providing wide-ranging improved technologies (Fentahun, 2016). In Ethiopia, the National Agricultural Research System (NARS) consists of federal research institutions and Regional Agricultural Research Institutes (RARIs), with over 71 research centers across different agro-ecologies. In addition, over 33 regional and federal colleges and universities engage in agricultural research as part of NARS. Moreover, NGOs, private sectors, and CGIAR centers also support agricultural research programs. Most notable achievements of the Ethiopian agricultural research system, among others, have been releasing more than 1,540 improved crop varieties (EAA, 2022) along with production packages in 149 crops. In addition to this, the Ethiopian Agricultural Research Institute (EIAR) has also developed several technologies in areas of livestock management, natural resource management, agricultural mechanization, and protocols in biotechnology research.

It is reported that these technologies contribute to improving the livelihoods of farmers specifically and the agriculture sector in general. The NARS in Ethiopia addresses a wide range of agroecologies and large numbers of commodities, aiming to address primarily food security. Moreover, it targets technologies for industry purposes and export markets. NARS is mainly funded by the government, although the support of international research institutes, NGOs and the private sector is quite meaningful. The income generated by the NARS to support the research system is not common in Ethiopia, which challenges the continuation of research activities and their multidimensional economic impact due to financial constraints. Generally, the NARS in Ethiopia lacks the commercial wing to support the research system.

The Agricultural and Rural Development (ARD) policy strongly recommends commercialization of the agriculture research system in Ethiopia to contribute to the agriculture sector self-reliant and competent. Commercialization is the process by which products, services, and technologies are introduced to the market for sale. From an international development perspective, this is an important pathway to providing smallholder farmers access to transformational innovations. The development process of commercialization includes a wide range of activities that includes conducting market research (assessing demand, market potential, etc.), designing and establishing processes and facilities to produce the product at scale, building a supply chain, determining distribution channels and related logistics, designing and implementing a marketing strategy (including customer segmentation and pricing strategy), and complying with regulations (ICAR, 2014). If product development is successful, it will ultimately result in a commercially viable product, service, or technology that can be made readily available in the marketplace (USAID, 2017).

The policy shifts the system to be inclusive of both public and private entities, requiring stakeholder registration before research service provision. It emphasizes the development of competitive, problem-solving technologies tailored to regional needs and a demand-driven approach. The policy mandates active involvement of the private sector in technology development and the establishment of an independent regulatory system for technology release and registration. It also introduces a royalty fee payment system to incentivize a dynamic research system. The reforms target three main areas: commercialization of public agricultural research, promotion of a pluralistic research system, and enhancement of intellectual property rights and royalty systems.

Efforts have been made to develop mechanisms to make the research system commercialized (Ayana *et al.,* 2023). Most of the recommendations are commodity-specific and don't cover a wide range of the agricultural sector. This study was conducted with the objective to provide context-specific recommendations to successfully commercialize the agricultural research system in Ethiopia.

2. Materials and Methods

The assessment engaged the participation of experts in revising the existing literature, analyzing the information gathered through different means, interviewing key informants and participating in exposure visits to learn from international experience. The information accessed using various approaches was further validated and analyzed.

2.1. Desk review

The study employed a team of senior experts organized in the form of Technical Taskforce Committee (TC) to review the available documents. TC comprises experts from NARS, ILRI and ATI. The TC was conducted desk review to gather evidence on current situation of Ethiopian agricultural research from secondary sources. Moreover, the TC visited selected institutions actively engage in agricultural research, including public research institutes, universities, CGIAR centers and private companies.

2.2. Key informant Interviews

Key informant interview was conducted by a team of experts from Analytics Department of ATI. The analytic team together with the ATI policy team prepared the interview document considering the international experience and the national context. The questionnaire was further validated in consultation with the Policy Unit of the Ministry of Agriculture. Interviewees were from EIAR centers (Kulumsa, Jimma and Debre Zeit) and universities (Bahir Dar, Hawassa, Jimma). Moreover, data were collected from participants to assess the potential of commercialization in the Ethiopian agricultural research system. The analytic case studies were conducted at three ARCs and on four commodities. These research centers were chosen for the in-depth analysis due to their strong research practices on the selected commodities. The selected research centers and the corresponding commodities include Debre Zeit ARC (teff and poultry), Kulumsa ARC (wheat), and Jimma ARC (coffee).

2.3. International benchmarking

The study employed two approaches to learn best experience from international benchmarking. The first approach was reviewing international practices with support of the Food and Agriculture Organization (FAO), Ethiopia country office. With mutual arrangement with ATI, FAO was assigned to gather and analyze the best international practices in relation to the commercialization of agricultural research outputs and services. The second one was facilitation of learning visits to counties. In this regard, a team of experts were visited Brazil, mainly the Brazilian Agricultural Research Corporation (EMBRAPA). The aim of the visit was to facilitate knowledge exchange between Ethiopian agricultural researchers and policymakers with the Brazilian counterparts, and to identify best practices that can be considered in the Ethiopian context. Furthermore, the visit aimed to explore innovative ways of agricultural research practices in Brazil, including policy instruments, institutional set up, roles of

actors, technology generation strategies, and capacity building such as human resources and facilities. The visit mission also intended to gain a comprehensive understanding on key success factors and regulatory frameworks about the commercialization of agricultural research, the mechanisms for revenue generation and utilization, and the protection of IPR including the royalty fee system.

3. Results and discussion

3.1. Investment in agricultural R&D

In absolute nominal terms, Ethiopia's investment in agricultural R&D has shown long-term growth. However, in real terms and compared to other countries, Ethiopia's investment in agricultural R&D remains low, resulting in weak research capacity, low outputs and hindered agricultural development. The results in Figure 1 (a) further shows that Ethiopia's agricultural research intensity has declined from- 0.49% of agricultural GDP in 2004 to 0.29% in 2016 and projected to decline to 0.19% in 2023, well below the New Partnership for Agricultural Development (NEPAD) target of 1% (Beintema and Haregewoin, 2018).

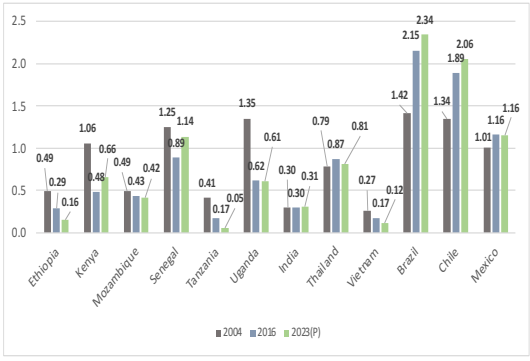


Figure 1 (a)

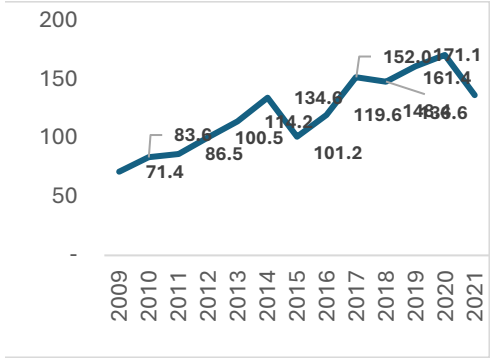


Figure 1 (b)

Figure 1. Total spending on agricultural research (as % agricultural GDP)
Source: Estimation based on ASTI database

As of 2016, Ethiopia invested 161.2 million constant 2011 PPP dollars in agricultural R&D, more than doubling the 56.5 million PPP dollars invested in 2000. While this trend is confirmed by the Monitoring and Analyzing Food and Agricultural Policies (MAFAP) database, the most recent available figure shows a 20% drop in 2021. In Ethiopia, public agricultural research institutions rely on government funding, loans, and donor assistance (EIAR, 2023). Whereas the experience of South Africa shows that the sources of funding/revenue is very diverse, including government grants, sales of goods in agricultural services, rendering of services, royalty income, rental of facilities and equipment, recoveries, dividends, donations, and interest on investments (ARC, 2023). Similarly, the Philippines research system has accessed finance for R&D from multiple sources such as government funding, private sector investment, co-funding and

funding support from implementing agencies and international grants and aid (RPCP, 2010). The international experiences from the Indian Council for Agriculture Research, Brazilian Agricultural Research Corporation, and the South African Research Council show that, fund allocation from government is the primary source of funding for public agricultural research institutions (ARC, 2023; Gerard *et al.,* 2024; ASTI, IDB and EMBRAPA, 2016). However, in Ethiopia funding from the government is not sufficient to deliver the desired research outputs, strengthening the capacity of research facilities, and human resource development.

Despite this overall underinvestment, R&D investments in Ethiopia have generated up to 4.5 dollars in revenue for every dollar invested (Nin-Pratt & Magalhaes, 2018). A study by Asfaw (2018) showed that a 1% increase in expenditure on agricultural R&D resulted in a 5.8% increase in agricultural total factor productivity. This, in turn, increases growth in agriculture sector and real GDP by about 3.7% and 3.1% from the baseline (2009/10), respectively, demonstrating the sectoral and economy-wide impact of investment in agricultural R&D. Similar experience from South Africa also revealed that in 2022/23, the South Africa Research Council received a R1 billion government grant and generated additional revenue from sales of goods, rendering of services, income from royalties and blood vaccines, and rental of facilities and services amounting to R464.9 million (ARC, 2023).

3.2. Human resources capacity in agricultural research in Ethiopia

Insufficient R&D funding has led to weak research infrastructure and facilities, shortage of human resource development, and low operating expenditures, which ultimately stunt agricultural innovation and productivity. This trend has likely contributed to the public sector's limited capacity to retain skilled researchers, underscoring the need for long-term investment in capacity building. The human resource profile of the NARS shows that there is a significant shortage of PhD-qualified researchers in Ethiopia. The human resource profile trend shows that the proportion of PhD holders among researchers has decreased from 8% in 2016 to a projected 4% in 2023, with a heavy reliance on MSc and BSc-level researchers.

In 2022, the proportion of PhD, MSc and BSc holders in NARS accounted for 7.25%, 51.45% and 41.3% respectively (EIAR, 2023). Whereas the experiences in South Africa and Uganda show an increasing trend of PhD holders (ARC, 2023 and NARO, 2022). This implies that Ethiopia has one of the least-qualified pools of agricultural researchers in Africa (Beintema and Haregewoin, 2018). The implication of underinvestment on human resource and research infrastructure and facilities such as up-to-date approaches including digital tools and platforms has hampered the quality and quantity of research outputs, overall efficiency of the research system, and undermining the effectiveness of agricultural R&D in addressing critical challenges. Therefore, it is time to improve public investment in agricultural R&D and diversify alternative sources of funding.

In general, the above-mentioned facts vividly show that the NARS is staffed with inadequate number of qualified researchers specialized at PhD level. A further in-depth assessment of the specialization mix of researchers suggests NARS lack researchers specializing in the new biosciences critical for generating technologies and information required for achieving targets set out in the 10 years perspective plan of the MoA and beyond. It is therefore important that the country needs to aggressively invest in improving the qualifications of its junior researchers and maintain a good balance of the gender mix to ensure the continuity of supplying demand driven agricultural technologies.

3.3. Policy, legal, and institutional environments

The coordination among various actors involved in agricultural research, whether directly or indirectly, was not formalized and supported by a legal framework until the establishment of EARO in 1997 by Proclamation No. 79/1997. This proclamation grants right for using the internally generated revenues for accomplishing their legible missions.

The Ethiopian Agricultural Research Council (EARC) and its Secretariat (EARCS) was established in 2016 with the consent of the constituents of NARS according to the Council of Minsters Regulation No. 383/2016. Very recently, the rights and obligations of the Ethiopian Agricultural Research Secretariat were transferred to the newly established Ethiopian Institute of Agricultural Research (EIAR) according to the Proclamation No.1263/2021. The Regulation Number 527/2022 was enacted to define the powers and responsibilities of EIAR. The recent regulation allows the research institute to collect revenues; however, it does not allow them to use the revenue collected, rather they are obliged to deposit the accounts of government treasury.

At policy level, the new ARD Policy clearly stipulates the drive for commercialization of agricultural research wherein it implied the relevant policy instruments should be developed in line with the commercialization spirit. The existing institutional arrangements and organization structure of the public agricultural research institutions does not suit commercialization efforts and there is also no legal provision to use the revenues generated for the expansion of the mission entrusted to research institutions. This calls for comprehensive reforms both in legal environment and institutional arrangements to entertain the commercialization of the research products and services.

3.4. Private sector in agricultural research system

The private sector's involvement in the developing world remains inadequate. In developing countries, private companies mainly focus on providing input technologies, such as seeds, chemicals, and farm machinery, or technological services for agricultural production. These technologies are mostly developed in developed countries and then adapted and tested in developing countries. Private seed and chemical companies in

Ethiopia work with the NARS. However, there is no legal framework for governing linkages between the NARS, CGIAR centers, private companies, and professional associations involved in agricultural research. A Pluralistic Agricultural Research System (PARSE), therefore, needs a clear and comprehensive legal framework for effective governance.

The private sector in agricultural research system is less developed, if not non-existent. Some private players with interest in agriculture research have done collaborated research with EIAR, RARIs and Universities. It is evident that with an appropriate policy environment and other necessary supports, private sector could flourish in agricultural research and contribute to strengthened agricultural technologies disseminations.

3.5. Intellectual property right in Ethiopia

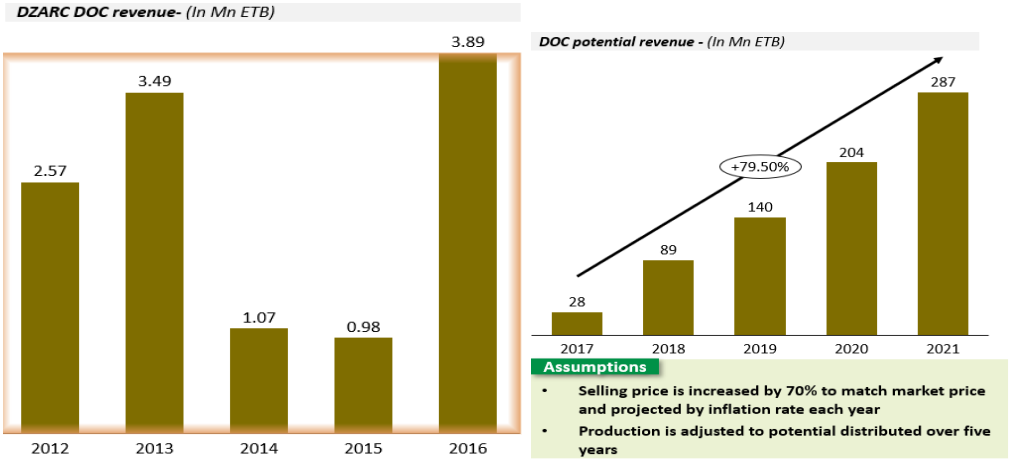
The IPR status in Ethiopia can be described in two phases as Non-plant IPR and Plant Related IPR or Plant Breeder Right (PBR) issues. Ethiopia, as a member of World Intellectual Property Organization (WIPO), is obliged to comply with the treaties on Intellectual Property. To protect the Intellectual Properties (IPs), Ethiopia incorporated provisions of IP on the national Constitution, Article 40(2). Based on this provision, the country enacted laws in different aspects of Intellectual property. For instance, Proclamation on Inventions, Minor Inventions and Industrial Designs, plant breeders' proclamation, proclamations on copy right, trademark and others (EIAR. 2016). Though PBR rights enacted, it lacks comprehensiveness does not fully address the current need for safeguarding IPRs. However, the implementation has not yet realized that significantly affects commercialization.

3.6. Prospects and potential of commercialization in agricultural research

Analytic case studies conducted by ATI at three ARCs and on four commodities show that research centers possess untapped potential that could be turned into growth factors and transformation through commercializing research outputs and related services. With appropriate adjustment and investment, research centers could uncover the untapped potential through commercializing research outputs and services and generate stream of revenue that could be used for strengthening their capacity and expanding their outreach.

An in-depth analysis on tef, poultry, wheat and coffee research indicates that there is a real opportunity for the research centers to generate millions in revenues. What it takes is adjusting to business practices through selecting the marketable aspect of the research activities and adopting the right commercialization model to drive commercialization. Public research centers have been funded from government treasure and significant levels of inefficiencies characterize their way of business making. There is also confusion among research centers on how to utilize the revenues generated citing there is no clear procedure or legal grounds to retain the income generated from sales of research outputs and related services. The research centers

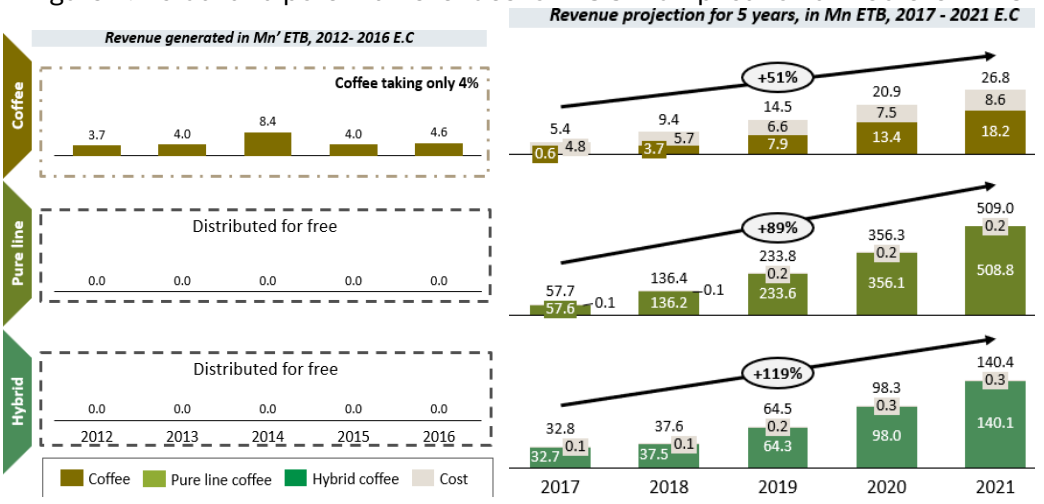
under consideration have potentially marketable outputs such as Day-Old Chicken (DOC), breeder parent stock, manure, feed, seed, by products, laboratory, consultancy, and mechanization trainings. Figures 2 and 3 display the potential of revenue from DOC and coffee seedlings through commercialization in the Ethiopian agricultural research system, respectively.



a) Actual revenue from DOC b) The potential revenue from DOC

Source: ATI, 2025

Figure 2. Actual and potential revenues for DOC multiplication at Debrezeit ARC



a) Actual coffee revenue generated b) Projected coffee revenue potential

Source: ATI, 2025

Figure 3. Coffee seedlings production status and potential capacity

3.7. Agricultural research funding schemes from global best practices

Governments create an enabling environment through formulating legal framework and needed support for implementation. Based on the international experiences, the

following alternative funding mechanism could be explored and adapted to Ethiopia's context.

Forge Public-Private Partnerships (PPP): are more widespread in agricultural research than in other agricultural sectors, especially in developing countries (Rai *et al.,* 2017). PPP may involve joint research projects, technology transfer agreements, or co-investment in research infrastructure (CropLife International 2009). The experiences of PPP in Brazil, Uganda, and India are good examples to take lesson. EMBRAPA also forged partnership with private sector companies, fostering a collaborative approach to agricultural R&D and supporting competitive grant programs to address both local and global agricultural challenges. EMBRAPA also has experience in collaborative funding to finance collaborative projects in 1) Productivity Enhancing Technologies; 2) Natural resource management improvement; 3) Policy, institutional and market strengthening and knowledge management; and 4) Smallholder and poverty-alleviation targeted technologies. In Uganda, Public private partnership between National Agricultural Research Organization (NARO) and Farm Inputs Care Centre Ltd to multiply and distribute certified high-quality maize, rice, cotton and sorghum seeds. Similarly, the Indian Council for Agricultural Research (ICAR): has established contractual relationships with public and private seed companies, collecting royalty payments from these companies. This strategy has significantly boosted its revenue. Public-private partnership in India falls under three areas: private distribution of public technologies through licensing of the public research output to private sector for commercialization; private purchase of public research services (e.g use of public sector infrastructure for testing of private- sector products for agronomic performance and biosafety); and public-private collaborative research partnerships (Hall *et al.,* 2001).

Revenue Generation and Retention through commercialization: Commercializing core technology products and services offers strong feasibility and control over funds, with moderate setup costs. The revenue generated needs to be retained by research institutions to ensure financial sustainability and efficiency. The experience of India, Brazil, and South Africa are good examples to take good lesson. ICAR's research institutes retain a portion of their generated revenue, providing a direct incentive for innovation and commercialization. This model has enabled ICAR to sustain and expand its research initiatives, fostering continuous agricultural development and technological advancements. Similarly, EMBRAPA generates a range of technological products and services, which are typically transferred at cost. It employs a variety of revenue generation mechanisms, including technology licensing, seed sales, and consultancy services. EMBRAPA retains a significant portion of this revenue, reinvesting it in further research and development. This model has proven sustainable and effective in promoting continuous innovation. EMBRAPA's ability to generate and retain revenue has enabled it to expand its research capabilities, improve infrastructure, and enhance human resource development. The experience of Uganda also shows that, as a result of commercialization policy, in 2022, nine new seed varieties were commercialized under the PPP and more than 200 contract farmers (individuals and

groups) with land of 16–60 ha participated in seed multiplication; Royalties from breeding activities generated (25% of total profit), which was reinvested in research, and the revenue generated from the public private partnership between NARO and Farm Inputs Care Centre Ltd in Uganda, 25% of the profit returned to NARO as royalty payments, which was reinvested in research (NARO, 2023).

Competitive Research Grants: The Department of Science and Technology - Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (DOST- PCAARRD), ICAR and EMBRAPA support competitive grant programs to support agricultural research projects across various disciplines. These grants are awarded based on merit and are aimed at addressing key national and international agricultural challenges. The competitive nature of these grants ensures that only the most promising and impactful research projects receive funding, fostering innovation and advancements in the agricultural sector.

4. Conclusion and Recommendations

The present study reveals that the Ethiopian agricultural research system is operating below capacity, with an untapped potential of generating revenue in hundreds of millions. The research system could leverage other potentials to diversify revenue streams including training, laboratory, consultancy and mechanization services. The return on investment on R&D for the national socio-economic growth is imperative. It is also evident that different countries deployed alternative funding mechanisms from different sources to reduce the burden on public funding and ensure sustainability of research systems. Therefore, this study recommends the Ethiopian agricultural systems to consider should include alternative interventions to increase the revenues and support the research activities. These include the diversification of alternative funding sources, supporting the commercialization of research outputs, implementation of the revenue retention waivers, encouraging the private sector participation, and implementation of the IPR and royalty fee collection mechanisms.

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Modernizing Cooperatives to Drive Agricultural Transformation in Ethiopia: A Policy Brief

Shimekit Maru* and Reta wegary

Ethiopian Agricultural Transformation Institute (ATI), P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding Author: shimekit.maru@ati.gov.et

Abstract

Cooperatives are fundamental to Ethiopia's agricultural sector, playing a key role in supporting smallholder farmers and pastoralists. They provide critical services such as access to agricultural inputs, mechanization, savings and credit facilities, and product marketing, while also enabling value addition. By fostering collective bargaining power and economies of scale, cooperatives empower smallholders to better participate in markets and improve their livelihoods. Over 107,000 registered cooperatives nationwide, they remain a central force for rural development despite facing significant operational and structural challenges. The objective of policy brief outlines key reform areas and actionable recommendations to enhance cooperative autonomy, efficiency, service delivery, and financial inclusion ensuring cooperatives fulfill their transformative potential in Ethiopia's agricultural sector. Key findings from a comprehensive diagnostic study reveal that many cooperatives lack a business-oriented structure, operate with insufficient capital, and face operational challenges due to their small size and limited scale. To effectively address these issues, a coordinated and cooperative reform effort is essential, with a strong emphasis on the directions of the revised Agriculture and Rural Development Policy. The proposed cooperative reform includes strengthening the legal and structural framework, enhancing financial capacity through dedicated funds and cooperative targeted banks, cooperative governance, and regulatory frameworks, promoting variant institutional frameworks, and modernizing cooperative governance. Strengthening oversight mechanisms are crucial for revitalizing the cooperative sector.

Keywords: Autonomy, member participation, rural development, structural framework

1. Introduction

Cooperatives are fundamental to Ethiopia's agricultural sector, playing a key role in supporting smallholder farmers and pastoralists. They provide critical services such as access to agricultural inputs, mechanization, savings and credit facilities, and product marketing, while also enabling value addition. By fostering collective bargaining power and economies of scale, cooperatives empower smallholders to better participate in markets and improve their livelihoods. The revised Agriculture and Rural Development (ARD) policy identifies Cooperative Modernization as a priority, focusing on autonomy, professional management, structural flexibility, expanded financing, and stronger oversight.

Cooperatives support smallholder farmers and pastoralists by delivering key services

such as the supply and distribution of agricultural inputs and technologies, agricultural mechanization services, savings, credit facilities, domestic and international marketing of agricultural products. Additionally, cooperatives provide critical value additions services, including aggregation, storage, warehousing, grading, sorting, and packaging, which help ensure product quality, reduce unnecessary market intermediaries, and enable farmers to secure better prices. Formal cooperatives have existed in Ethiopia since 1960, engaged in the production and marketing of various agricultural commodities. However, the performance of cooperatives has been declining even with the support of multiple policy instruments. To address these issues, the revised Agricultural and Rural Development (ARD) policy prioritizes "Cooperatives Modernization," focusing on five key reform areas: ensuring autonomy, promoting professional management, enabling structural flexibility, expanding financing options, and strengthening oversight systems, thereby strengthening the role of cooperatives in Ethiopia's rural and agricultural transformation. Therefore, the policy brief aims to recommend realistic solutions to address the critical challenges affecting the performance of cooperatives in line with the revised Agriculture and Rural Development (ARD) policy directions.

2. Materials and Methods

A comprehensive assessment was made on cooperatives' existing structures, focusing on governance, operational, and financial challenges. Evidence was drawn from document reviews, legal framework analysis, and extensive stakeholder consultations, reinforced by case studies and international learning visits. Building on this foundation, the solution design prioritizes stronger cooperative organization, enhanced governance and business practices, improved access to finance, and legislative reforms that promote a more business-friendly environment.

3. Result and Discussions

Over 107,000 registered cooperatives have existed in Ethiopia, comprising 106,497 Primary Cooperatives (PCs), 403 Unions, and 5 Federations, with the majority concentrated in the Oromia, Amhara, and former SNNP regions. Although the sector has seen significant growth in terms of numbers and capital, many cooperatives continue to face critical operational challenges. The cooperative governance model in Ethiopia is structured around three main bodies: the General Assembly, the Board of Directors, and recruited staff. Decision-making is distributed among these entities to ensure collective accountability. However, despite the policy emphasis and presence of a legal framework under Proclamation No. 985/2012, the practical implementation of governance principles remains weak.

Ethiopian cooperatives face a wide range of interrelated challenges that hinder their growth, competitiveness, and sustainability. One of the primary issues is that cooperatives are not structured in a business-oriented manner. Their roles and objectives are often unclear, and several cooperatives were established without a

proper business plan or feasibility studies and often lack a clear organizational development vision. Additionally, there is little differentiation between the functions of primary cooperatives and unions, with both often engaging in similar activities, contrary to the intended complementary role of unions. These shortcomings, coupled with limited capital, weak governance structures, and low overall performance, entail the effectiveness and sustainability of cooperatives. Structural inefficiencies, poor institutional capacity, and limited oversight continue to hinder the cooperative movement's ability to contribute meaningfully to economic development and member empowerment.

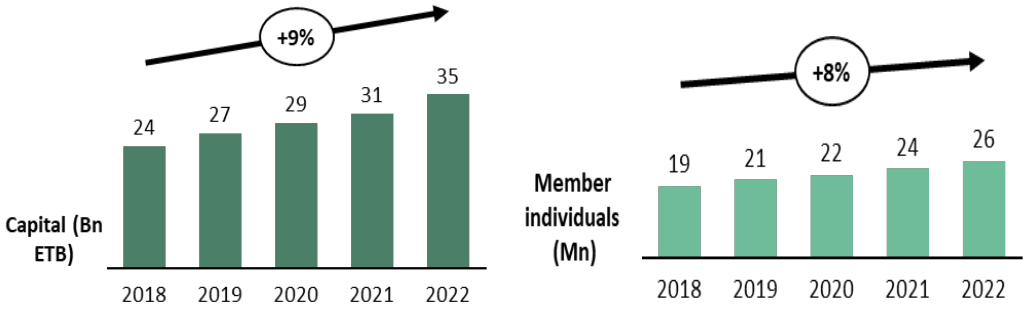

Figure 28, Trends in the growth of Cooperative individual members, and their capital base (2018-2022)

Government interference further weakens cooperatives by limiting their autonomy in decision-making. Promotion agencies are heavily involved in hiring and managing staff, setting restrictive rules, controlling pricing, and determining market access, leaving cooperatives unable to operate independently. Management capacity is another critical constraint. Despite the availability of cooperative-related training in universities and a series of on-the-job training, most committee members lack the necessary qualifications and practical experience. Communication and documentation systems are weak, operational protocols are missing, and control committees are often nonfunctional. Member engagement is also low, with poor participation in general assemblies and decision-making processes. The cooperative members and capital have grown significantly in recent years, with the growth rate of 8% and 9%, respectively, over the last five years (Figure 1).

However, the financial constraints are widespread, with most cooperatives struggling to raise sufficient capital internally. Limited and low-value shares, inadequate retained earnings, and low voluntary savings from members all contribute to weak capital bases. For instance, 66% of primary cooperatives operate with less than 100,000 ETB in capital, and 23% of unions operate with less than 1 million ETB.

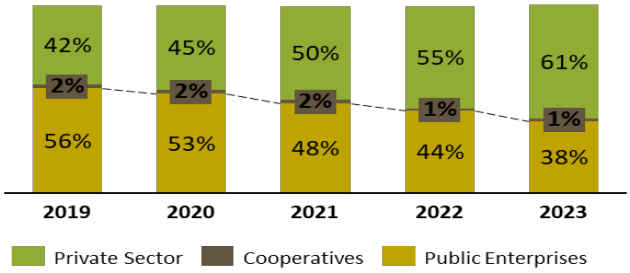

Figure 29. Cooperatives' share of outstanding loans by the banking system (2019-2023)

Financial institutions show reluctance to lend to cooperatives because many lack the necessary collateral, audited financial reports, and solid financial records. Consequently, cooperatives receive less than 2% of outstanding loans from the banking system, while the private sector and public enterprises share 48% and 50.5% respectively. This limited access to finance is driven by cooperatives' weak business profiles and inadequate financial management.

Operational challenges are deeply rooted in the cooperative business model. The small size and limited scale of cooperatives reduce their bargaining power and competitiveness, often forcing them to sell raw produce to private processors instead of engaging in value addition. Limited revenue streams restrict their ability to invest in processing, branding, technology, and attracting skilled personnel. Moreover, cooperatives lack the autonomy to set prices, expand geographically, or form joint ventures, restrictions that prevent them from seizing market opportunities and leveraging economies of scale. Poor decision-making, often stemming from limited business insight among committee members, leads to inefficient use of resources and further diminishes their ability to compete effectively. Cooperative decision-making inefficiencies stem from the tension between inclusiveness and decisiveness in democratic processes, diverse member interests, and governance capacity limitations. These dynamics are well described in cooperative governance and decision-making literature and affirmed in this study, emphasizing consensus challenges, collective action dilemmas, and the need for structured decision protocols to enhance effectiveness and legitimacy.

Oversight and accountability mechanisms are also weak. Less than 20% of cooperatives are regularly audited due to the limited capacity of promotion agencies and the large number of cooperatives nationwide. The regulatory framework governing cooperatives is incomplete. Although Proclamation 985/2012 provides a legal foundation, it lacks detailed regulations and directives necessary for practical implementation. Weak institutional arrangements and insufficient staffing in promotion agencies further hinder the ability to effectively audit, inspect, and regulate over 107,000 cooperatives across the country.

4. Conclusion and Recommendations

The modernization of cooperatives in Ethiopia is a critical pillar for achieving inclusive rural and agricultural development under the revised ARD policy. The findings clearly show that although cooperatives in Ethiopia have expanded significantly in both number, capital and legal recognition, their operational effectiveness, financial sustainability, and governance quality remain critically weak. Structural inefficiencies, lack of business orientation, weak institutional support, and inadequate regulatory frameworks have hindered their ability to function as viable, competitive entities in the economy.

The policy recommendations highlight that without comprehensive reform spanning legal restructuring, financial empowerment, professional governance, and institutional realignment, the cooperative sector will continue to underperform and fail to deliver on its potential for rural transformation. Therefore, the modernization of cooperatives must be pursued as a national priority. This requires a coordinated and committed effort from government, development partners, NGOs, and cooperative members themselves. Strengthening autonomy, enabling financial innovation, ensuring accountability, and promoting professionalism are not just desirable interventions; they are necessary conditions for transforming cooperatives into engines of inclusive agricultural growth and rural prosperity in Ethiopia.

To address the wide-ranging challenges facing Ethiopian cooperatives, an effective policy implementation and systemic reforms are required across five key focus areas: ensuring autonomy, promoting professional management, enabling structural flexibility, expanding financing options, and strengthening oversight systems. Some challenges are cross-cutting and span legal, institutional, and operational dimensions.

Key recommendations

The legal and structural framework must be strengthened. This includes detailing legal requirements and supporting the merger and consolidation of primary cooperatives to form stronger, more competitive entities. Cooperatives should also be allowed to expand their operations and membership into areas where no cooperatives currently exist. When forming new cooperatives, a thorough feasibility study, including capital requirements, should be mandatory to ensure viability.

Establishing a Coop Bank, a coop fund, credit guarantee schemes, and pooling international funds will improve cooperatives' access to finance. Financial capacity should be enhanced through mechanisms such as the establishment of a dedicated cooperative fund and a cooperative bank. Establishing a coop fund, credit guarantee schemes, and pooling international funds will improve cooperatives' access to finance. Additionally, cooperatives should be allowed to accept outside equity in the form of preferred shares with non-voting rights. However, this should only be permitted in financially sound cooperatives and requires proper legal inclusion in the cooperative

proclamation.

Governance and regulatory frameworks need urgent reform. Certification systems should be updated to incorporate sector-specific assessment criteria and to evaluate the sustainability of cooperatives. The existing Proclamation 985/2016 should be revised and endorsed through strong lobbying efforts to create a sense of urgency. Furthermore, a new regulation and the missing directives must be developed and adopted to complete the regulatory framework.

Institutional consistency and professionalization are key. There is a need to develop a consistent structural arrangement for cooperative promotion agencies across all regions and to establish an independent national apex body for cooperative oversight.

Hiring certified auditors and leveraging external auditors will increase the number of cooperatives audited annually. Therefore, the audit systems should also be reformed by strengthening provisions within the law and encouraging audits by chartered professionals. The government should avoid conducting direct audits and instead allow cooperatives to engage certified external auditors independently.

Unions and federations must shift from input distribution and output aggregation to value addition and processing. Cooperative governance should be modernized by including provisions for appointing qualified experts and independent directors to their boards. This would improve leadership quality and strategic decision-making, enabling cooperatives to operate more effectively in a competitive market environment.

Modelling the current Land Suitability and Future Dynamics for Coffee (*Coffea arabica* L.) Cultivation under Climate Change Scenarios in Western Ethiopia with MaxEnt Model

Tesfaye Akafu[1*], Diriba Korecha[2], Weyessa Garedew[1] and Abayineh Amare[1]

[1]Jimma University, College of Agriculture and Veterinary Medicine, Jimma, Oromia, Ethiopia
[2]University of California Santa Barbara, Santa Barbara, California, USA
[*]Corresponding author: *tesfayeakafu65@gmail.com*

Abstract

Coffee is the world's most popular beverage crop and the second-most traded commodity next to petroleum products. However, the production of coffee is heavily dependent on specific environmental conditions, making it vulnerable to the effects of climate change. Therefore, studying coffee crop responses to climatic conditions is crucial to developing strategies to support coffee crop resilience. This study aimed to model the current land suitability and future dynamics for Coffea arabica cultivation under climate change scenarios in the West Wallaga Zone, Western Ethiopia. The study used bioclimatic variables and the current occurrence data of Coffea arabica. Modeling was done for current and anticipated shared socioeconomic pathways (SSP) at intermediate (SSP245), and very high (SSP585) emissions scenarios for 2050 and 2070. ArcGIS was used for data processing, whereas MaxEnt (Maximum Entropy) model for predicting suitability. The results showed 5294.30 km^2 (50.8%) of the total land in the area is presently suitable for Coffea arabica cultivation. The model predicts that 19–24% of the current suitable coffee cultivation areas may become unsuitable, while 20–22% more areas may become suitable for coffee cultivation. Based on the MaxEnt model, the total suitable land for Coffea arabica cultivation could be reduced by 40.3 km² and 136.11 km² in 2050 under the SSP245 and SSP585 scenarios, respectively. The model simulation for 2070 indicates declines of 164.6 km^2, and 177.8 km^2 in SSP245, and SSP585, respectively. Therefore, designing a plan for species conservation and implementing climate change adaptation strategies are essential for sustaining the suitability of existing coffee growing areas.

Keywords: Climate change, Coffea arabica L., MaxEnt, Modeling, Land Suitability

1. Introduction

Coffee is the world's most popular beverage crop and the second most traded commodity next to petroleum products (DaMatta *et al*., 2019). Nearly 25 million farmers globally, the majority of whom are smallholders, are engaged in the cultivation of coffee across an estimated 80 tropical countries (Bermudez *et al*., 2022). While there are more than 125 coffee varieties existing worldwide (Davis and Rakotonasolo, 2021), Arabica (*Coffea Arabica* Linnaeus) and Robusta (*Coffea Canophera*) coffee varieties account for 99% of worldwide bean production (DaMatta, 2018). These are also responsible for 57% and 43% of the world coffee market, respectively (ICO 2022).

Coffee production requires specific climatic conditions (DaMatta *et al*., 2019). Temperature and precipitation patterns are crucial factors that have a significant impact on coffee production. This sensitivity to climatic conditions makes coffee, particularly *C. arabica,* highly vulnerable to the negative impacts of climate change (Bunn *et al.,* 2015). The optimal average mean annual temperature ranges for *C. arabica* lie between 18–23 °C (Davis *et al*., 2012). The rainfall requirements are between 1600–2000 mm (Chemura *et al*., 2015), with a dry period ranging from 3–4 months near to harvest period (DaMatta *et al*., 2018).

In Ethiopia, the average yearly temperature has risen by 1 °C over the last forty years, with significant fluctuations in precipitations trends showing increases in some regions and decreases in others. Projection of the high emission scenario revealed that mean annual temperature will rise by 1.8 °C and 3.7 °C by 2050 and 2080, respectively, accompanied by an overall increase of total annual precipitations from 3 mm to 6 mm (USAID, 2024). Nevertheless, there is high uncertainty in predicted precipitation distributions in space and time (MFA, 2018). Some coffee varieties may experience heightened climatic pressures in their natural habitats, as they are particularly vulnerable to the effects of climate change (IPCC 2022; DaMatta *et al*., 2019). Therefore, examining the response of coffee crops to climatic conditions is crucial in developing strategies to support the crop's resilience towards the adverse impacts of climate change.

One way to investigate how climate change affects coffee production in coffee-producing regions is to employ contemporary analytical instruments like Species Distribution Modeling (SDM). SDM identifies species occurrence and predicts suitability of a habitat across space and time (Elith and Leathwick, 2009). Recent national models show Arabica coffee cultivation areas in Ethiopia may decrease (Moat *et al*., 2017; Davis *et al*., 2012), while regional studies suggest varied outcomes (Ovalle-Rivera *et al*., 2015). This indicates that the findings are not easily generalizable regionally, with some contradicting each other and mask national context studies. As a result, greater identification of the impact of climate change on particular locations or local coffee areas is required.

West Wallaga coffee is a wet-processed varietal grown in Western Ethiopia at elevations between 1493 m and 1798 meter above sea level (m.a.s.l.). In this zone, farmers and stakeholders in the coffee industry have been noticing a gradual decline in overall coffee yield. Good harvests, which were previously a yearly occurrence, have now become sporadic, manifesting only once every second or even third year (Moat *et al*., 2017). Furthermore, (Moat *et al*., 2017) made a prediction that the coffee-producing area of Wallaga is likely to face a high level of vulnerability to climate change. However, a more recent investigation by (Chemura *et al*., 2021) provided contrasting insights. The contrasting conclusions of the two studies underscore the complexity and uncertainty often associated with climate change projections, emphasizing the critical need for sustained research to fully understand and prepare for the potential consequences

facing the study area. Thus, this study aimed to modeling potential land suitability dynamics for *Coffea Arabica* Linnaeus cultivation under climate change in the West Wallaga Zone, Western Ethiopia.

2. Material and Methods

2.1. Study site

The research was conducted in the West Wallaga Zone, located in western Ethiopia. The location of the study area is shown in Figure 1. The zone consists of 23 districts, with 20 rural and 3 urban administrations. Gimbi Town is the capital of the zone. The West Wallaga Zone situated between 9º 00' N latitude and 35º14'E longitude, bordered by Kelam Wallaga Zone to the west, Benishangul Gumuz Region to the north, and East Wallaga Zone to the east. It also adjoins Illu Abbaa Boora and Buno Bedele Zones, and Benishangul Gumuz region to the southeast. The zone covers an area of 10,430.28 km^2. According to Hurni (1998), the agroecology of the West Wallaga Zone is classified into three zones: lowland 19.1% (1100–1700 m), midland 78.4% (1701–2200 m), and highland 2.5% (2201–2850 m). The zone exhibits monomodal rainfall pattern, with the wet season occurring from June to September (Korecha and Barnston, 2007).

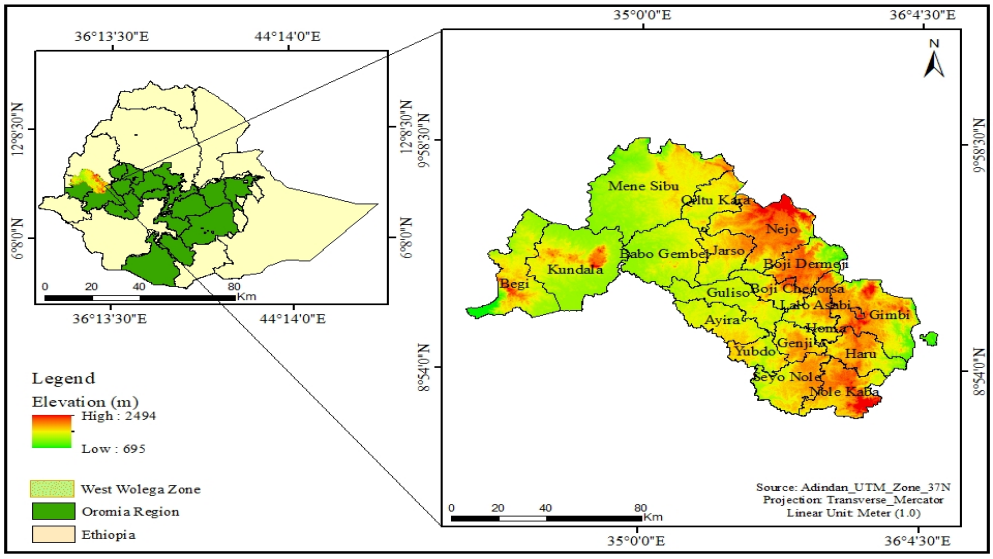

Figure 30. Map of the study area

2.2. Modelling approach

The study used MaxEnt 3.4.4 to model *C. arabica* cultivation areas. In the Maxent model, we used bioclimatic variables as environmental predictors, and coffee

occurrence point as sample data. Out of the 477 coffee presence, 75% were used for model training, while the remaining 25% for model validation. The model was run using 11 bioclimatic variables in 15 replicates for current and projected climates in 2050 and 2070, considering moderate (SSP245), and very high (SSP585) emissions scenarios.

2.2.1. Sampling methods

Purposive and simple random sampling methods were used for this study. Primarily, the West Wallaga Zone was purposively selected because of its high coffee production potential, and no previous research had been conducted. Secondly, simple random sampling was used to collect the GPS point of *Coffea arabica* farms from the entire districts where coffee naturally grows.

2.2.2. Data collection

Five hundred geographic coordinate points were collected from where *C. arabica* naturally occurs in the west Wallaga zone. To map the current land suitability, climate data averaged over 30 years (1970–2000), was downloaded from WorldClim at 30 arc-second (~1 km^2) spatial resolution. The database contains 19 bioclimatic variables. To predict for the years of 2050 and 2070, variables from four Global Circulation Models (GCMs) in the Coupled Model Intercomparison Project Phase (CMIP6) were used. These includes HadGEM3-GC31-LL, ACCESS-CM2, INM-CM5-0, and the MRI-ESM2.

3. Result and Discussion

3.1. Model Evaluation

The model performance for the current, 2050 and 2070 suitability models is displayed in Figures 2 (a-e). The MaxEnt model consistently demonstrated accuracy and reliability, as reflected by the impressive range of Area under the curve (AUC) values between 0.77 and 0.78. These values underscore the model's exceptional performance in predicting the presence/absence of *C. arabica* distribution in various scenarios (Elith *et al*., 2006). These results corroborate the findings by (Jayakody *et al*., 2024).

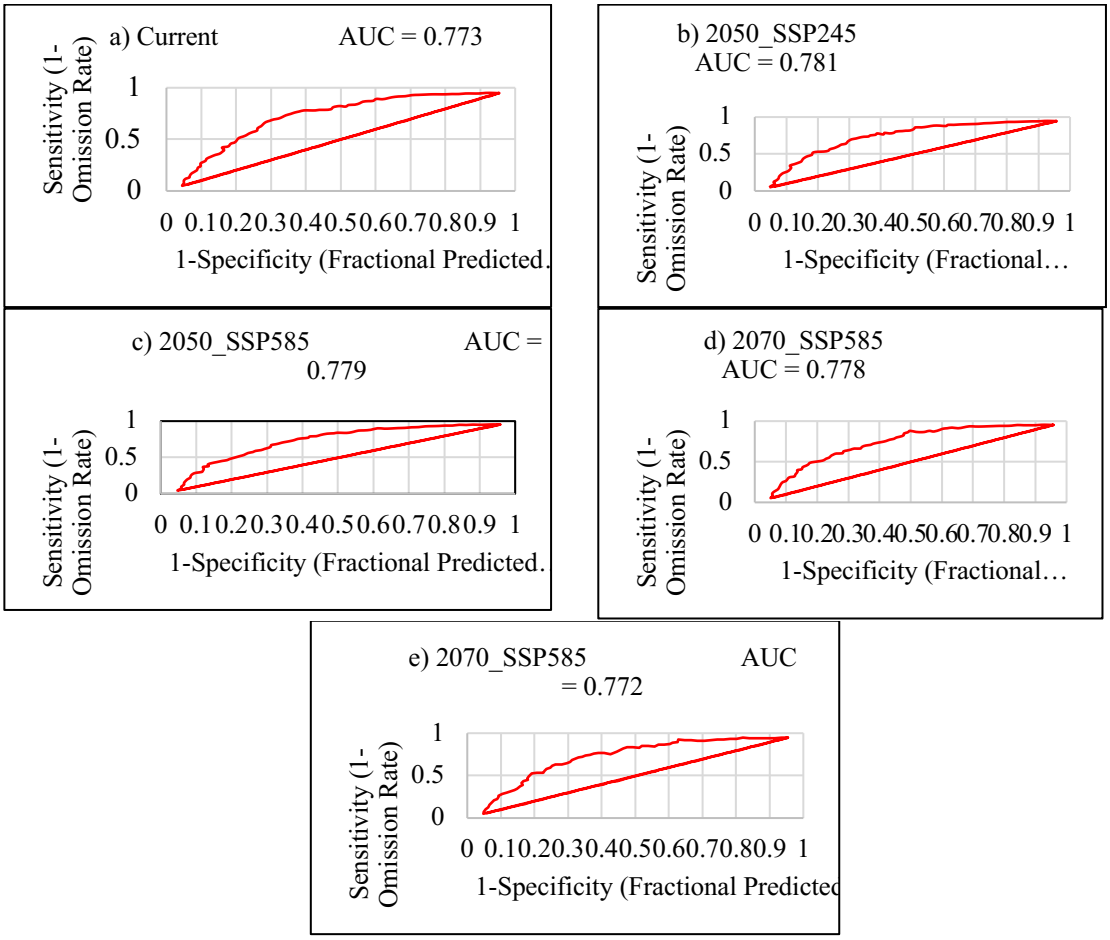

Figure 2. The ROC curve for the current and predicted suitability of *C. arabica* in the study area

3.2. Contribution of Environmental Variables

Table 1 displays environmental variables entered in the Maxent for model simulation and their predicted contributions under the climate change scenario. The maximum temperature of the warmest month and the mean diurnal range temperature are among the temperature variables that had the higher predictive contribution for the present and future coffee suitability models. Of the precipitation variable, precipitation in the coldest quarter was the most significant factor for land suitability prediction. Overall, temperature variables were a key factor in determining *C. arabica* cultivation suitability under all climate change scenarios. This aligns with previous studies by (Gomes *et al*., 2020) and (Bunn *et al*., 2015) documenting the importance of temperature in coffee distribution modeling.

Table 1. Estimates of bioclimatic variables' contributions to the MaxEnt model

Code	**Bioclimatic variables**	**Percentage contribution**				
		Current	**2050**		**2070**	
			SSP245	SSP585	SSP245	SSP585
BIO1	Annual Mean Temperature	0.7	4.1	7.8	2.9	4.1
BIO2	Mean Diurnal Range temperature	16.4	18.6	16.7	16.5	18.2
BIO3	Isothermality (BIO2/BIO7) (×100)	2.9	4.1	1.5	8.4	3.2
BIO4	Temperature Seasonality	4.3	9.1	10.2	9	9.6
BIO5	Max Temperature of Warmest Month	34.3	13.3	14.9	18.4	15.9
BIO7	Temperature Annual Range	5.5	0.9	2	2.1	1.5
BIO9	Mean Temperature of Driest Quarter	0.3	0.3	0.9	0.2	0.8
BIO12	Annual Precipitation	6.9	6.9	8.6	7.5	7
BIO14	Precipitation of Driest Month	13.7	14.9	15.3	13.2	14.3
BIO15	Precipitation Seasonality	6.2	2.9	1.8	6.6	0.8
BIO19	Precipitation of Coldest Quarter	8.8	24.9	20.3	15.2	24.6

3.3. Current and Future Suitability

Following prior research on the modeling of species distribution (Abebe *et al*., 2024; Ab Lah *et al*., 2021), we reclassified the suitability map into four suitability classes: <0.2 (unsuitable), 0.2–0.4 (low suitable), 0.4–0.6 (moderately suitable), and >0.6 (highly suitable). The distributions of coffee are shown in Figure 3a-e. In the current suitability map (Figure 3a), only 989.64 km^2 (9.5%) of the area is classified as high coffee suitability, followed by 2,743.90km^2 (26.3%) moderately suitable, 3,069.62 km^2 (29.4%) low suitable, and a large proportion of 3,627.98 km^2 (34.9%) of the study area falls under unsuitable. The model predictions presented in Figure 4b-e for 2050 and 2070 revealed varying distributions in climatic suitability for coffee cultivation. The results for all

climate change scenarios indicated significant potential for land transformation (Table 2). This result corroborates the findings of Davis *et al*., (2012).

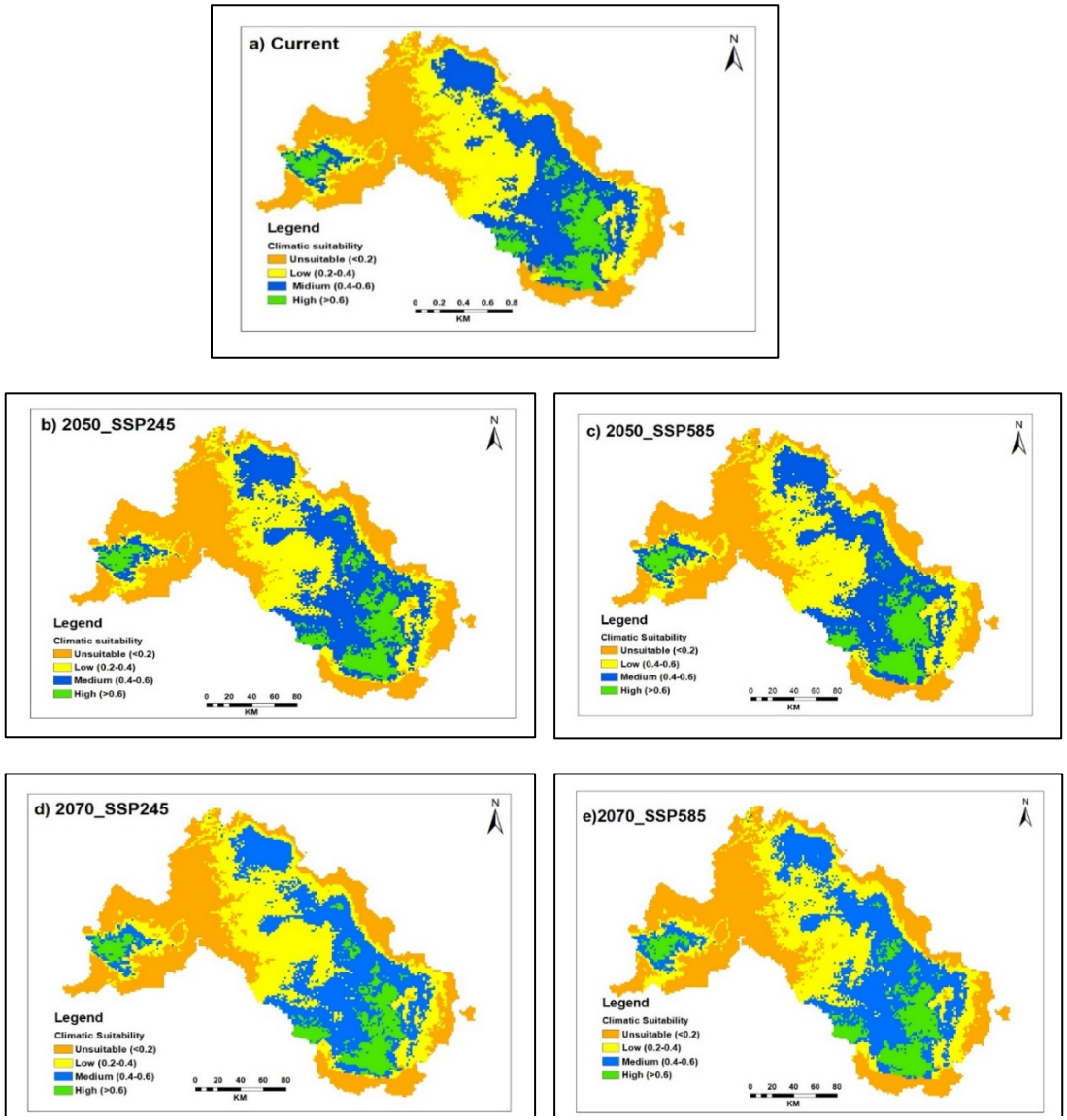

Figure 3. Current and future climatic suitability for *C. arabica* cultivation in the West Wallaga Zone, Western Ethiopia

Table 2. Coffee arabica suitability distribution under future climate change scenarios in the West Wallaga zone, Western Ethiopia

Period	Scenarios	Land suitability area in square kilometers and percentage			
		Unsuitable	Low suitable	Moderate suitable	High suitable

		km^2	%	km^2	%	km^2	%	km^2	%
2050	SSP245	3532.14	33.86	3143.23	30.13	2808.49	26.92	947.27	9.08
	SSP585	3659.93	35.09	2958.50	28.36	2862.66	27.44	950.05	9.11
2070	SSP245	3491.86	33.48	3181.43	30.50	2883.49	27.64	874.35	8.38
	SSP585	3614.79	34.65	2946.69	28.25	2932.11	28.11	937.55	8.99

3.4. Predicted suitability losses and gains

The predicted change in climate is likely to negatively impact the areas currently suitable for coffee cultivation. For the 2050, it is predicted that the present suitability would be lost by 19.15% and 21.78%, while it would be gained by 17.71% and 20.58% under SSP245 and SSP585, respectively. Conversely, it is suggested that 63.14%, and 57.64% of the area will remain stable under SSP245, and SSP585, respectively (Figure 5 a & b). The model projects that suitable areas could decline by 21.62%, and 24.26%, while it expects an increase of 20.76%, and 21.68% in suitable areas in 2070, under the SSP245, and SSP585 scenarios, respectively. Furthermore, the projections suggest about 57.62%, and 54.06%, is expected to remain unchanged by 2070 under the SSP245, and SSP585 scenarios, respectively (Figure 5 c & d).

3.5. Predicted change in total suitability areas

The land suitability areas for coffee cultivation under current and future climate change scenarios are shown in Figure 4. The logistic threshold values were used to reclassify the map into suitable and unsuitable areas. The classification system denotes that values falling below the designated threshold are believed unsuitable, whereas values above the specified threshold signify potential suitability for *C. arabica* cultivation (Merow *et al*., 2013). The land areas suitable for *C. arabica* cultivation could be reduced in all projected climate change scenarios as compared to the current suitable areas (Table 3). The reduction in areas suitable for *C. arabica* cultivation has also been documented at both regional and global levels (Gruter *et al*., 2022; Bunn *et al*., 2015).

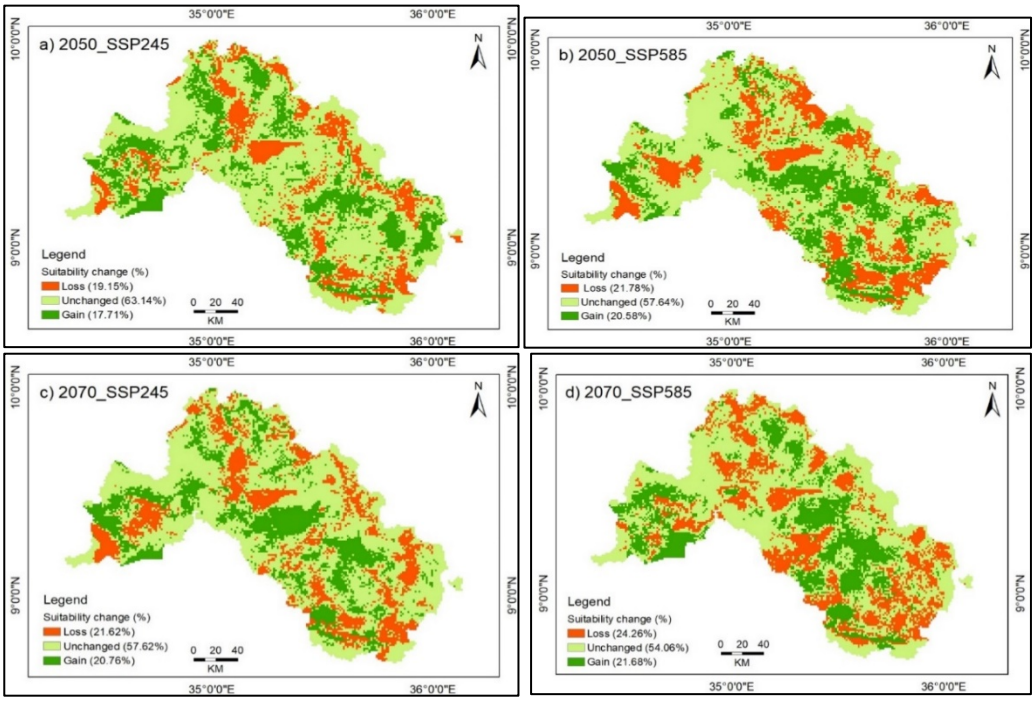

Figure 4. The predicted suitability changes for *Coffea arabica* cultivation under future climate change scenarios in the West Wallaga Zone, Western Ethiopia.

Table 3. Predicted total suitability changes in *Coffea arabica* cultivation compared to current areas in the West Wallaga zone, Western Ethiopia

Period	Scenarios	Total suitability area (km^2) and % of land				Total suitability change	
		Unsuitable		Suitable			
		Km^2	%	Km^2	%	Δ (Km^2)	Δ (%)
Current	Baseline	5135.98	49.25	5294.30	50.75	-	-
2050	SSP245	5176.25	49.63	5254.03	50.37	-40.28	0.38
	SSP585	5272.08	50.55	5158.20	49.45	-136.11	1.3
2070	SSP245	5300.55	50.82	5129.73	49.18	-164.58	1.57
	SSP585	5313.75	50.95	5116.53	49.05	-177.77	1.7

4. Conclusion and Recommendations

The research employed a MaxEnt model to map the current land suitability and future dynamics for *Coffea arabica* cultivation under climate change scenarios. The study used bioclimatic variables and coffee presence data for the suitability model. Based on the MaxEnt output, approximately half of the lands in the West Wallaga Zone were identified as currently suitable for *Coffea arabica* cultivation. The projected result

revealed that while current coffee cultivation areas may see a significant decline in their suitability, certain areas that were presently unsuitable for coffee cultivation will become suitable. In addition, a decrease in the total land area appropriate for coffee cultivation has been detected across all climate change scenarios in comparison to the current total land considered suitable for coffee production. This decline may affect both the quality and quantity of coffee production. Overall, the sustainability of *Coffea arabica* cultivation is facing significant challenges in a substantial portion of the coffee-growing areas within the west Wallaga Zone. This highlights the need to prioritize the development and implementation of effective adaptation and mitigation measures to ensure the long-term sustainability of coffee cultivation in the face of evolving climatic conditions.

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Mapping and Spatial Analysis of Some Soil Parameters in Domte Wodye District, Southern Ethiopia

Alemu Lelago* and Mesfin Bibiso

Wolaita Sodo University, Ethiopia
* Corresponding author: lelagoalemu@gmail.com

Abstract

The purpose of the study was to analyze soil spatial variability and map selected soil properties of agricultural soils in Domte Wodye district, Southern Ethiopia. For this study about 120 geo referenced soil samples were collected. Soil nutrients except organic matter (OM) were extracted with Mehlich-3 and measured with inductively coupled plasma spectrometer. Geo-statistical analysis was performed using ordinary kriging. Phosphorus (P) showed strong spatial dependence, while sulfur (S) and boron (B) showed weak dependence; all other properties showed moderate dependence. Soil pH ranged from 4.68 to 7.24 and about 88.75% of soils were acidic. Available P and S ranged from 3.15 to 49.83 ppm and 4.41 to 63.62 ppm, respectively; Approximately 91.25% soils were deficient in available P, and 100% were deficient in available S. Soil OM alternated from 0.66 to 6.07% and about 72.50% had low OM status. Exchangeable potassium (K), calcium (Ca) and magnesium (Mg) values ranged from 0.68 to 4.28, 5.1 to 18.62 and 1.17 to 3.75 cmolc kg^{-1}, respectively indicating that nearly all soils had enough of these cations. Extracted Fe, Mn, B and Cu ranged between 83.61 and 222.18, 118.47 and 400.56, 0.01 to 0.96 and 0.22 to 1.55 mg kg^{-1}, respectively. The semivariogram range for all studied soil properties confirmed that it was sufficient to hook their spatial variability. This study indicated that most of the analyzed soils were deficient in P, S, Cu and B showing that they limit the higher production of common crops. Therefore, the blended (NPSBCu), lime for strongly acidic soils of the study area, and organic matter should be applied to boost the agricultural productivity.

Keywords: Agricultural soils, Macronutrients, Mehlich-3, Micronutrients, Ordinary kringing

1. Introduction

Regardless of the diversity of the agricultural products and crop species in Ethiopia, the production performance is still below optimum level (Alemu *et al*., 2016a). Many researchers reported that application of unbalanced and low rate of chemical fertilizer is among the factors responsible for the poor performance of Ethiopian agriculture (Spielman *et al*., 2013; Tadesse *et al*., 2013). Therefore, in order to increase crop production and productivity and to realize government's strategy of commercialization

of smallholder agriculture, recommending exact rate of site and crop specific balanced fertilizer which is derived from calibration of soil test and crop response is very vital.

Inorganic fertilizers have been the important tools to overcome soil fertility problems, and they are also responsible for a large part of the food production increases in worldwide (Sanchez *et al.*, 2000). Also, about 30 to 50% of crop yield increment is related to application of commercial fertilizers (Santra, *et al.,* 2008). The application of blanket fertilizer rate recommendation in all parts of country and agro ecological zone indicates the existence of little or no information on the fertility status of Ethiopia's soils since 2014. Low soil fertility highly affects the growth and development of cereal crops as compared to other crops (Dwivedi *et al*., 2003). As a result, they cannot produce maximum yields unless sufficient nutrients are available. The knowledge about the nutrient requirement of the crop and the nutrient supplying power of the soil is very important to determine proper application rates of plant nutrients.

Information on spatial variability of soil nutrients is important for sustainable management of soil fertility. Among many geostatistical methods ordinary kriging is widely used to map spatial variation of soil fertility. According to Ismaili and Ahmed (2014), ordinary kriging (using either exponential or spherical models) is more accurate for predicting the spatial patterns of the soil properties pH, OM, P, and K than the two other methods (IDW and splines), because it provides a higher level of prediction accuracy (Song *et al*., 2011)http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0099695.

In Ethiopia, initial results of demonstration of blended fertilizers that include N, P, K, S, Zn and B conducted across 25,000 smallholder farms indicate that yield increases between 15-85% can be achieved. In some areas, where soil fertility maps did not show apparent Potassium deficiency, adding additional Potassium produces a bump in yields showing the need to revisit the K critical limits set for various soils (ATA, 2015).

The crop yield cannot be enhanced without judicious use of macronutrient fertilizers to overcome existing deficiencies/imbalances. Knowledge about an up-to-date status of soil macronutrients and mapping their spatial distribution play an important role in site-specific fertilizer recommendation to increase production and productivity of the agricultural sectors on sustainable basis. However, information on the status and spatial distribution of soil macronutrients is limited for Wolaita zone. Therefore, the objectives of this research were assessing and mapping the status and spatial distribution of some soil fertility parameters for Domote Wodye of Wolaita Zone.

2. Material and Methods

2.1. Study Area

This research was conducted in Domte Wodye district of Wolaita Zone, Southern Nations, Nationalities, and Peoples' Region (SNNPR) of Ethiopia in 2018. The

geographical locations of the research were 037°35'30" - 037°58'36"E and 06°57'20" - 07°04'31"N. Also, the elevation of it ranges between 1473 to 2873 meters above sea level (m.a.s.l).

2.2. Soil Sample Collection Preparation and Soil Laboratory Analysis

Surface soil samples (0-20 cm for annual crops and 0-50 cm for perennial crops) were collected through composite sampling technique where sampling points were determined by setting pre-defined sampling points. Based on the topography and soil variability 120 composite soil samples were collected from September to November 2020. Samples were taken from locations having similar soil types, topography, and land use history or land utilization type (LUT). For each composite sample, about 1kg of representative composite soil sample was collected and logged into properly labeled plastic sample bag. The collected soil samples were air-dried, grounded and passed through 2 mm sieves and 0.5 mm diameter sieve for analysis all other soil properties and organic carbon, respectively. All soil parameters were analyzed at Hort Coop Soil Laboratory in Debre Ziet, Ethiopia.

Soil pH in H_2O (1:2) was determined by using digital pH meter with glass electrode. The particle size distribution was measured according to Van Reeuwijk (1993) and Walkley and Black (1934) the method was used to detect organic carbon. Organic matter content was obtained by multiplying the OC content by a factor of 1.724. Available sulfur (S) and phosphorus (P), exchangeable basic cations (calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K)), and micronutrients (iron (Fe), zinc (Zn), manganese (Mn), boron (B), copper (Cu), and molybdenum (Mo)) were extracted according to Mehlich (1984) and were detected with their respective wave length range by Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Soil cation exchange capacity was measured according to the method described by Van Reeuwijk (1993).

2.3. Soil Fertility Mapping

Soil fertility parameters for non-sampled sites were predicted using Ordinary kriging based on the nearby surveyed data. The soil parameters were interpolated across the study area using the geo-statistical model and their spatial prediction were evaluated. For every soil property the experimental variogram was calculated. ArcGIS software version 10 tool was used for mapping of predicted soil attributes. After kriging was carried out for selected soil parameters and macronutrients, their classes were defined as very low, low, optimum, high and very high classes from the map based on the EthioSIS critical levels and other appropriate methods. The spatial dependence between samples was also determined considering the relationship between the nugget effect (C_0) and sill ($C_0 + C_1$) expressed in percentage: 0-25% high, 25-75% medium and 75-100% low spatial dependence between samples, as proposed by Cambardella *et al.,* (1994).

3. Results and Discussion

3.1. Soil reaction (pH)

The measured pH values indicated that the agricultural soils of study area varied from 4.68 to 7.24 indicating wide range of variation (Table 1). These differences may be due to variations in soil formation processes and factors, land use type, and soil fertility management practices. According to EthioSIS (2014), 12.50, 76.25, and 11.25 % of the samples in the study area were found to be strongly acidic (<5.5), moderately acidic (5.6-6.5) and neutral (6.6-7.3), respectively. The pH status map showed that spherical model is the best fit for the semivariogram of soil pH. Alemu *et al*., 2016; Fanuel, 2015; Tesfahunegn *et al.,* 2011 reported similar findings. The sampling intermission in this study was sufficient to capture the spatial variability in soil pH since the range value (700 m) which is greater than average sampling distance (500m). The nugget-to-sill ratio which is calculated from semivariogram was 0.74 which revealed the moderate spatial dependence of soil pH (Table 1).

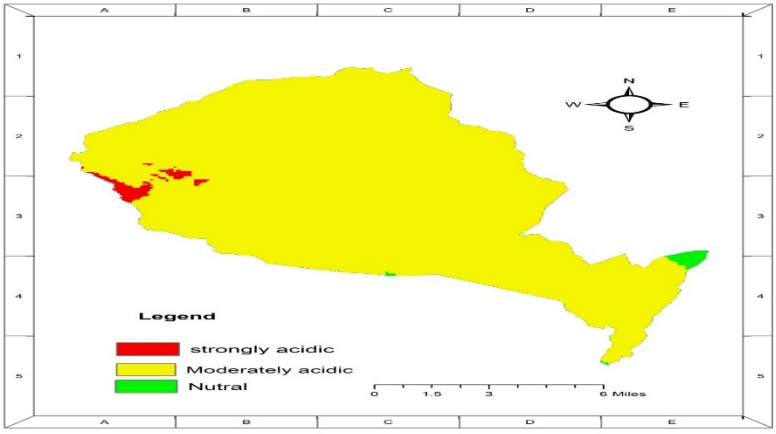

Figure 1. pH map of the study area.

It was found that most of the soils were acidic (strongly and moderately) in reaction. The highest altitude zones of the study area were found to be acidic (Figure 1) which can be explained by moderate leaching of exchangeable bases, acidic parent material, decomposition of OM, harvesting of high yielding (Yihenew *et al.,* 2015 and Abreha *et al.,* 2012). Therefore, the raising of soil pH using different treatments is vital to enhance crop yield.

3.2. Available phosphorus

Mehlich-3 extracted available phosphorus content varied from 3.15 to 49.83 ppm in the study area. This indicates that soils of the study showed a wide range of variability in P status. The variability in available P contents of soils might be due to different soil management practices, specifically, inherent soil fertility status, type and rate of

organic and inorganic fertilizers used in cultivated lands. According to EthioSIS (2014) for Mehlich-3 extractable P, 77.50, 13.75 and 8.75% of soils of study were very low, low and optimum, respectively.

This result indicates that, in general, the majority (91.25%) of soils not sufficient in P (Figure 2). The reasons for low P status in the soils may be due to low pH (acidity), the intensive cropping system, imbalanced use of fertilizer and nutrient mining. These finding agrees with the report of Sahlemedhin and Ahmed, (1983) who reported P deficiency was very severe in the acidic soils of the southern, southwestern and western Ethiopia due to fixation of P with Al^{3+} and Fe^{3+}.

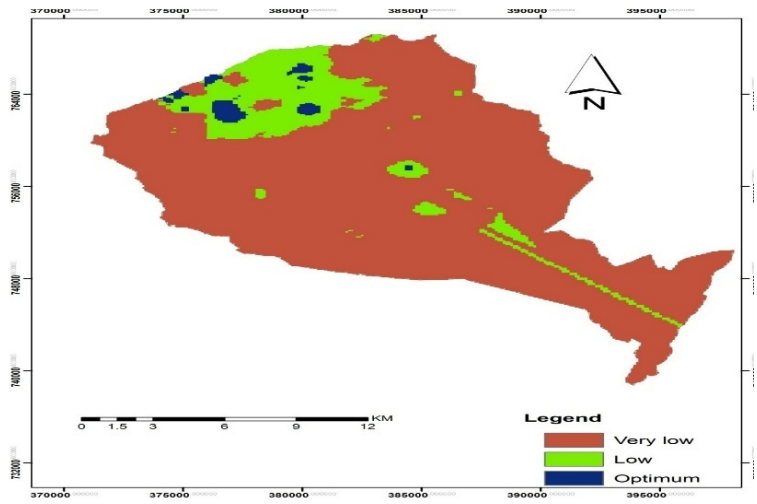

Figure 2. Map of available P in the study area.

Table 1. Descriptive and geo statistics of selected soil fertility parameters

Descriptive statistics	**pH** _	**P** ppm	**S**	**OM** %	**TN**	**C:N** _
Minimum	4.68	3.15	4.41	0.66	0.0003	0.77
Maximum	7.24	49.83	63.62	6.07	0.5100	40.75
Mean	6.10	10.77	9.26	2.72	0.1137[b]	9.84[a]
Median	6.17	7.80	7.00	2.49	0.1241	10.50
Std Dev	0.46	9.43	3.33	1.59	0.1041	7.53
CV (%)	7.56	87. 57	42.61	58.51	89.00	76.52
Model	Spherical	Spherical	Gaussian	Exponential	Exponential	_
Range(m)	750	902.50	700.33	950	1062.5	_
$C_0/(C1+C_0)$	0.74	0.12	0.99	0.45	0.55	_
SD	Moderate	Strong	Weak	Moderate	Moderate	_

N=number of total samples per woreda, SD= spatial dependence, *** =P<0,001, ** =P<0, 01, NS, non-significant Means with similar letters are not statistically significant at P<0.01

3.3. Available Sulphur

The available S content ranged from 4.41 to 63.62 ppm in agricultural soils of study area (Table 1). According to rating of available S status by EthioSIS (2014), among agricultural soils of study area 86.25, 8.75 and 5.00% were rated as very low, low and optimum category, respectively (Figure 3). The prediction map for S was prepared with Ordinary kriging by using Gaussian model which showed best fit for S on some variogram after log transforming data (Figure 3). Range value for available S data were 700.33 m which is greater than average sampling distance (500 m), confirming that sampling interval in this study was adequate to capture the variability in soil available S. The nugget-to-sill ratio was 0.99 which proves that spatial dependence of S data between samples is weak.

Generally, this finding revealed that all agricultural soils of the study areas were deficient (< 20 mg kg-1) in S content (EthioSIS, 2014). Sulphur is taken up by most grain crops in amounts similar to those of P, from 10 to 30 kg/ha (Weil and Mughogho, 2000) but there has not been any practice of external addition of this nutrient in the study areas. A positive correlation (r=0.4) was observed between organic carbon and available S component. This relationship existed because most of the part of S is associated with organic matter (Nor, 1981). Supporting this finding, Itanna (2005) and Tekalign and Haque (1991) reported that the lower content of OM is one of the causes of lower content of S in Ethiopian soils.

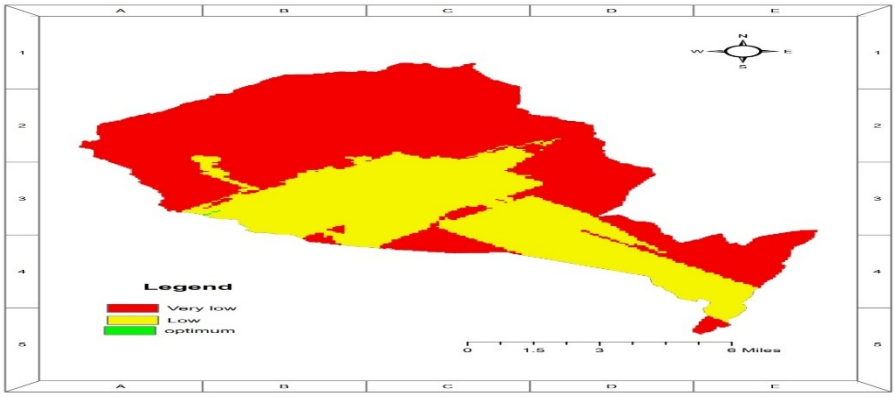

Figure 3. Map of the available S in the study area.

3.4. Organic matter

The organic matter content of the soils on research sites were ranged from 0.66 to 6.07% and was highly variable (CV>50%) (Table 1). However, in this study, the range

value for OM, 950 m, that is greater than the average distance between samples (500m) indicates that it is sufficient to arrest variability in soil OM. Status of soil OM oscillated from very low to optimum for agricultural soils of research site based on rating suggested by EthioSIS (2014).The exponential model was found to be the best fit for OM on semivariogram. The nugget-to-sill ratio was 0.45, confirming a moderate spatial dependence for OM data between samples was moderate.

According to EthioSIS (2014) 33.75, 28.75 and 37.50% of soil samples were very low (<2%), low(2-3%) and optimum (3-7%), respectively. The most of soil samples analyzed (62.50%) had below optimum level OM (Figure 4). This has led to drastic decline of crop productivity and in order to boost the crop productivity, it is recommended to apply organic residues as important source of nutrient to these agricultural fields.

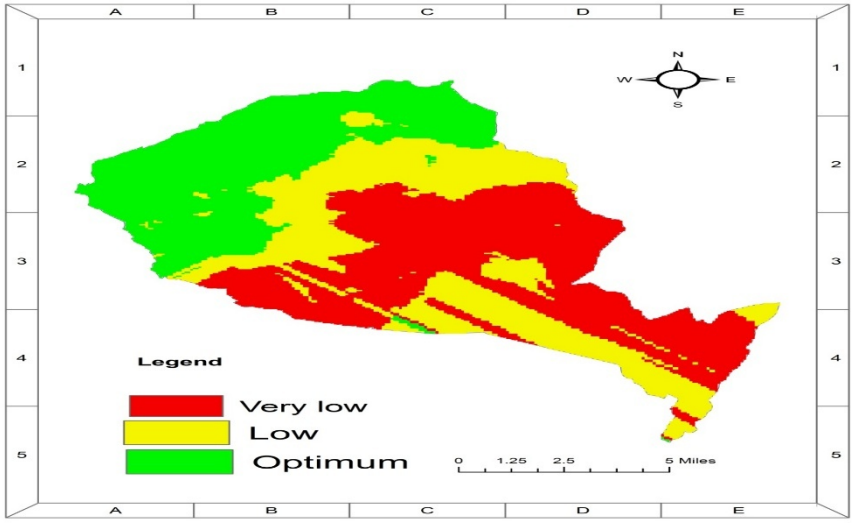

Figure 4. OM map of the study area.

3.5. Exchangeable Bases (Ca, Mg, Na and K), Cation Exchange Capacity (CEC)

Table 2 indicated that the Mehlich-3 extractable K ranged between 0.68 and 4.28 Cmol (+) kg^{-1}. According to EthioSIS (2014), 50%, 30% and 20% of soil samples were optimum, high and very high in exchangeable K status. It was found that sampling distance is enough to capture the variability K in the agricultural land because the range 900.65 m indicates that greater than average distance. The sill to nugget ratio 0.15 indicates that the spatial dependence of K is strong.

Regardless of the high amount of exchangeable K, fertilizers containing K should be applied to boost crop productivity since most of soils of the study areas are clay soils (Alemu *et al*., 2016) that could fix exchangeable K and reduce its availability for plants,

and continuous crop response to K fertilizer has been proved by the massive potash fertilizer demonstrations conducted in the country (EthioSIS, 2014).

Exchangeable Ca^{2+} varied from 5.1 to 18.62 cmolc kg^{-1} in study area. The spatial distribution of Ca^{2+} is shown in Figure 6, which is mapped by interpolation with ordinary kriging and spherical model was found to be the best fit for Ca^{2+}. The nugget to sill ratio 0.75 shows that the spatial dependence of Ca^{2+} was weak. The range value of 928.89 m indicates that the average distance between soil samples is adequate enough to capture variability in Ca^{2}. Figure5. shows that in terms of area coverage according to critical level set by Maria and Yost (2006), 33.5 and 66.5% of the agricultural land were found to be medium (5-10 cmolc kg^{-1})and high(10-20 cmolc kg^{-1}), respectively. Based on the critical values set by FAO (2006) amount of exchangeable Ca was above its respective critical values in all soils.

As indicated in Table 3 exchangeable Mg^{2+} varied from 1.17 to 3.75 cmolc kg^{-1} in the study area (wit h mean value of 2.33. As per the critical values set by FAO (2006), amount of exchangeable Mg^{2+} was above its respective critical value (1.0 cmolc kg^{-1}) in all of soil samples collected from the study areas. As shows Figure 4C the extent In terms of area, 87.50% and 12.5%) was optimum (1-3 cmolc kg^{-})and high(3-8 cmolc kg)$^{-}$, respectively. The range was 1152.98 m for Mg^{2+} data. Spatial dependence was weak having nugget to sill ratio 0.71.

The mean relative abundance of basic cations in the exchange complex was in order of Ca > Mg > K > Na for soils collected from the study areas. This could be related to the charge density where the divalent cations (Ca and Mg) have higher affinity towards the colloidal sites than monovalent cations (K and Na).

The cation exchange capacity (CEC) varied from low to high and ranged between 6.94 and 36.29 meq/100g with mean value of 16.47 for study areas. High CV value (31.81%) indicates that the soils of the study area vary widely in CEC. This might be due to differences in soil type, land use type and soil fertility management. According to London (2014), 37.50, 56.25 and 6.25 % of soil samples collected from the study area are categorized as the low (5-15), moderate (15 - 25), high (25-40) and very high (>40cmol (+) kg^{-1}), respectively in CEC, indicating that about 93.75% of the soils have adequate basic cations to support plant growth. The high value of CEC in the soils is mainly due to high clay content and the predominance of 2:1 clay mineral. Also, positive and significant correlation (r = 0.37) between pH and CEC of the soil samples collected from the study area was observed.

Table 2. Descriptive and geo statistics of exchangeable cataions

Descriptive Statistics	**Ca**	**Mg**	**K**	**Na**	**CEC**
	Cmol (+) kg^{-1}				
Minimum	5.08	1.17	0.68	0.07	6.94

Maximum	18.62	3.85	4.28	2.47	36.29
Mean	9.92	2.33	1.73	0.37	16.47
Median	9.28	2.31	1.54	0.17	16.07
Std Dev	3.13	0.51	0.20	0.06	5.24
CV (%)	31.55	21.89	42.87	16	31.81
Model	Spherical	Exponential	Gaussian	-	Spherical
Range	928.89	1152.98	900	-	851
$C_0/(C1+C_0)$	0.75	0.71	0.15	-	0.81
Spatial dependence	Weak	Weak	Strong	-	Weak

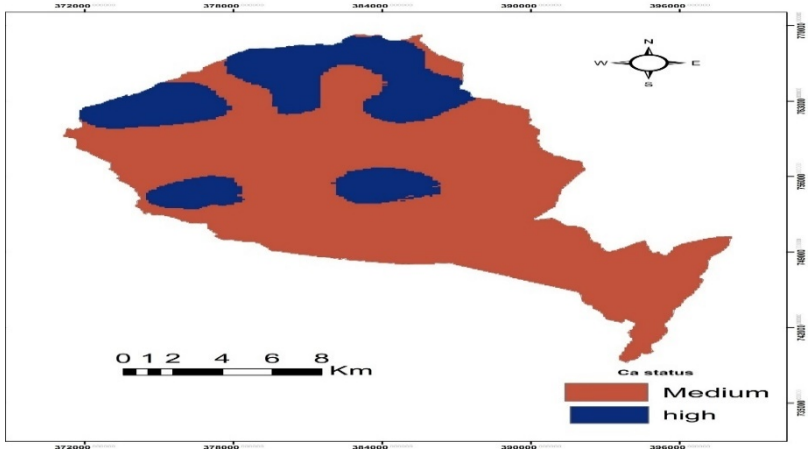

Figure 5. Ca map of the study area Iron (Fe).

Table 3 showed that the Mehlich-3 extractable Fe ranged between 83.61 and 222.18 mg kg $^{-1}$ with a mean of 158.02 mg kg^{-1}.

According to the critical level adopted by (EthioSIS, 2014), almost all agricultural soil of the study area, was found to be optimum (25-300 mg kg $^{-1}$) in Fe status since the map was not drawn here. However, exponential model was found to be the best fit for Fe data and range value for Fe is 979 m, which is greater than the average sampling distance (500m) in this study, indicating that it is enough to capture variability among Fe data in the study area. Similar to this result, (Fanuel, 2015) and (Alemu *et al*., 2016) reported that exponential model is the best to map Fe status. The nugget to sill ratio was 0.45 confirming that the existence of moderate spatial dependence between Fe data. It was observed that, in terms of area coverage, all of the agricultural lands were found to be optimum in available Fe status. Haque *et al*., (2000) also reported that Fe levels were usually adequate for Ethiopian soils.

Table 3. Descriptive and Geo statistics of soil micronutrients (B, Cu, Fe, Mn and Zn) in the study districts.

Descriptive Statistics	**Fe mg kg^{-1}**	**Zn**	**Mn**	**B**	**Cu**

Minimum	83.61	1.60	118.47	0.01	0.22
Maximum	222.18	27.53	400.56	0.96	1.55
Mean	158.02	10.22	248.79	0.16	0.56
Median	153.07	8.19	243.31	0.12	0.51
Std Dev	33.22	6.48	64.41	0.08	0.26
CV (%)	21.02	63.45	25.00	55.61	21.85
Model	Exponential	Exponential	-	Exponential	Exponential
Range (m)	979	1050	-	951	708
$C_0/(C1+C_0)$	0.45	0.45	-	0.81	0.51
Spatial dependence	Moderate	Moderate		Weak	Moderate

The laboratory results showed that the Mehlich-3 extractable Mn ranged between 118.47 and 400.56 mg kg^{-1} in agricultural soils collected from study areas (Table 3). According to Jones (2005), its concentration has got a level of toxicity to most of the crop species. This indicated that Mn toxicity is one of the factors that contributes to the low crop productivity and production in the study areas. Also, Mehlich-3 extractable B varied from 0.01 to 0.96 mg kg^{-1}, respectively (Table 3). The larger CV (>50%) indicates that the higher variability between B data. This higher variability is due to variation in landscape positions, management practices, land use types, soil type and inherent properties like texture and pH.

As shown in Figure 6, 96.25 and 3.75% of agricultural soils of the study area were respectively found to be very low (<0.5 mg kg^{-1}) and low (0.5- 0.8 mg kg^{-1}) in B status. The exponential model was found to be the best fit for B data. The range value 791m and nugget to sill ratio 0.81 indicates that the sampling average distance (500m) is enough to capture the variability in B status in the study area soils and the spatial structure for B is moderate, respectively. This revealed that nearly all agricultural soils of the study areas are below critical level in B status, and it is one of the crop yields limiting nutrient in the study areas. The results of this study align with those reported by, Fanuel (2015), Gezu (2015), Eyob (2014), and Wondosen and Sheleme (2011), who documented boron (B) deficiencies in certain soils of western and southern Ethiopia.

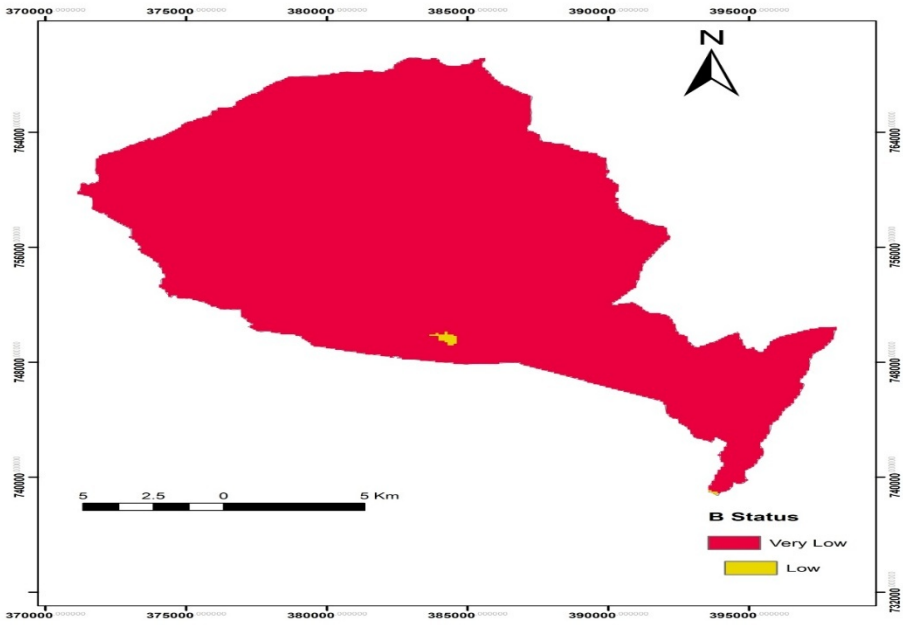

Figure 6. B map of the study area

The possible reasons for B deficiency in the study area may be due to loss of B through leaching in acidic soil, low B absorbing capacity of soils, low OM, continuous cultivation of soils, low B containing parent materials, lower application rate of manure and use of non B containing fertilizer (Gebeyaw, 2007). Generally, this finding revealed that B is deficient and it may be one of the limiting elements in all woredas of the study area since the deficiency of it affects the growing points of roots, shoots and young leaves and retard the uptake of calcium. Therefore, it is strongly recommended that B should be the part of blended fertilizer to boost the crop yield in the study area.

The Mehlich-3 extractable Cu ranged from 0.22 to 1.55 mg kg^{-1} in agricultural soils of study area with mean value of 0.56. According to (EthioSIS, 2014), 46.25, 42.50 and 11.25% were found in very low (<0.5), low (0.5-0.9) and optimum (0.9-10) category, respectively.

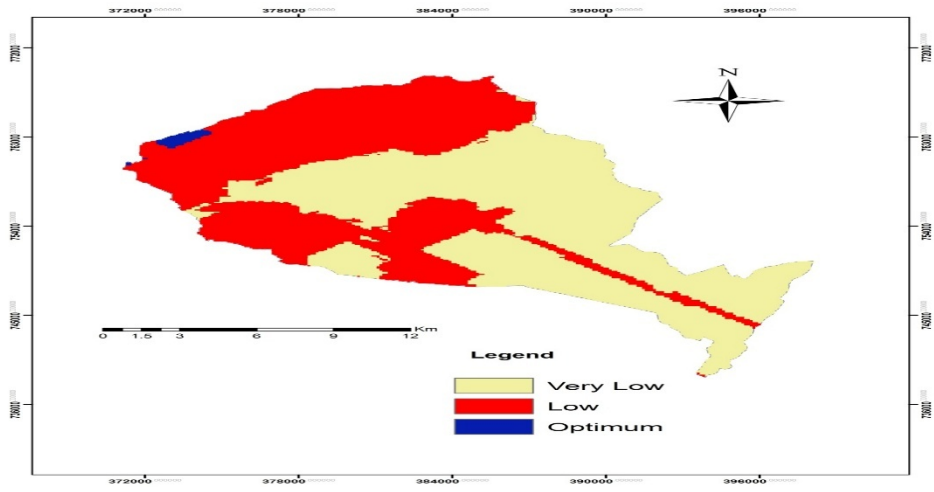

Figure 7. Cu map of the study area

4. Conclusion and Recommendations

This study indicated that there is wide spatial variation in soil pH, macro and micronutrients in different degree of spatial dependence. For this, the optimal sampling spacing identified in this study can be used and accurate for interpolation technique such as kriging can be used for detailed mapping of the soil properties. The pH of the soil varied from 4.68 to 7.24, indicting wide variation with status of strongly acidic to moderately alkaline. However, 88.75% of the soils were acidic. Therefore, appropriate treatment is recommended for both strongly acidic and moderately acidic soils. The plant available P status ranged from 3.15 to 49.83 ppm. But about 91.25% of analyzed soil samples were below the optimum level mainly due to the acidity of the soil reaction. Thus, site specific organic or inorganic P fertilizer sources are recommended to boost the agricultural productivity of the study areas. Available S ranged between 4.41 to 63.62 ppm but 95% of it were below optimum (very low and low) in available S status. Therefore, S should be the part of recommended blended or compound fertilizer. Exchangeable K ranged from 0.68 to 4.28 Cmol (+) kg^{-1} that were above or optimum in exchangeable K status.

This study revealed that Mehlich-3 extractable levels of Fe, Zn, and Mo in the soil were sufficient. The calculated Mn Availability Index (MnAI) exceeded the critical threshold, suggesting that Mn toxicity is prevalent. Extractable B and Cu concentrations were low, and to address key soil fertility limitations while promoting a steady increase in soil organic matter (OM), the application of NPSB and NPSBCu fertilizer types is recommended.

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Enhancing Agricultural Commercialization Through Digital Agricultural Extension and Advisory Services: Lessons from the 8028 Farmer's Hotline

Temesgen Gebeyehu*, Kidistie Bizuneh, Habtamu Hailemariam, Ezedin Abdela, Elsabet Tesfa, Abenet Solomon, Asbunela Yesuf, Haftamu Tesfay, and Chimdo Anchala

Agricultural Transformation Institute (ATI), Digital Agriculture and Finance Program, P.O. Box 708, Addis Ababa, Ethiopia

*Corresponding author: *Temesgen.Gebeyehu@ati.gov.et; tngebeyehu@gmail.com*

Abstract

Digital technologies are transforming agriculture in Low- and Middle-Income Countries (LMICs), with nearly 1,400 digital agriculture solutions serving 50 million users. These tools optimize farming practices, increase production, and promote sustainability. In Ethiopia, the government has prioritized digital agriculture as part of the Digital Ethiopia 2025 strategy, aiming to enhance productivity, market linkages, and resilience. However, challenges such as limited infrastructure, low digital literacy, and policy gaps persist. To address limited outreach of agricultural extension services, the Ethiopian Agricultural Transformation Institute (ATI), in partnership with the Ministry of Agriculture (MoA), the Ethiopian Institute of Agricultural Research (EIAR) and Ethio Telecom, launched the "8028 Farmer's Hotline (FHL)" in 2014. This digital service uses Interactive Voice Response (IVR) and Short Message Service (SMS) to provide real-time agricultural information. By December 2024, it reached 6.9 million registered farmers, including 2.78 million from Agricultural Commercialization Cluster (ACC) woredas, generating over 66 million interactions. This report evaluates the hotline's contributions to ACC and lessons learned by analysing data from platform dashboards, project reports, and monitoring assessments. Findings show the hotline has significantly enhanced smallholder farmers' productivity by improving knowledge of agronomic practices, promoting certified seeds and digital solutions, and supporting the ACC Program from 2019–2024. It contributed to a 23% increase in access to extension services and raised average yields of key grain commodities by up to 86%. Additionally, it has played a key role in shaping Ethiopia's digital agriculture roadmaps and strengthening extension and advisory services. The report also highlights challenges, including poor mobile network coverage and low digital literacy, and offers recommendations for improving digital advisory services to support Ethiopia's agricultural transformation.

Keywords: Agricultural Commercialization Cluster (ACC) Program, Artificial Intelligence, Early Warning, IVR/SMS, Smallholder farmers

1. Introduction

Digital technologies are increasingly pivotal in transforming agriculture, particularly in Low- and Middle-Income Countries (LMICs). According to the "State of the Digital Agriculture Sector" report by Beanstalk AgTech, nearly 1,400 digital agriculture (D4Ag)

solutions are active across LMICs, collectively serving approximately 50 million users, which equates to about 10% of smallholder farming households in these regions (Beanstalk AgTech, 2023). These technologies encompass a range of tools, including Big Data Analytics, GPS navigation, and Artificial Intelligence (AI), all aimed at enhancing farming efficiency, reducing costs, and increasing production. For instance, AI-powered technologies assist farmers in precision agriculture by optimizing yields and managing water usage, thereby promoting sustainability even amidst climate change challenges.

Ethiopia has also recognized the potential of digital technologies in agriculture by prioritizing it as one of the four key pillars in the Digital Ethiopia 2025 strategy (FDRE, 2020). This strategy underscores the role of digital tools in improving productivity, market linkages, and resilience within the agricultural sector. However, challenges such as limited digital infrastructure, low digital literacy among farmers, and the need for supportive policies persist. Addressing these issues is crucial for maximizing the potential of digital technologies in agriculture and ensuring inclusive growth within the sector.

A key enabler of agricultural transformation is an effective agricultural extension system that provides farmers with timely, research-based agronomic advice. However, Ethiopia's extension services face challenges, including a high farmer-to-extension agent ratio, limited mobility of development agents (DAs), and communication barriers, especially in remote areas (Davis *et al*., 2010). Despite government investments in public extension services, smallholder farmers continue to struggle with accessing timely information on improved farming practices, pest and disease outbreaks, and market trends (Berhane *et al*., 2018). Traditional extension methods that rely on in-person training and field visits can be slow and inefficient, causing delays in the adoption of new technologies (Gashaw *et al*., 2022). To overcome these challenges, scalable digital solutions are essential to complement existing extension systems and improve the dissemination of critical agricultural information (FAO, 2021).

In response, the Ethiopian Agricultural Transformation Institute (ATI), in partnership with the Ministry of Agriculture (MoA), the Ethiopian Institute of Agricultural Research (EIAR), and Ethio Telecom, developed the 8028 Farmers Hotline (FHL). Launched nationwide in 2014, the digital platform utilizes Interactive Voice Response (IVR) and Short Message Service (SMS) technologies to provide real-time access to agronomic best practices, early warning alerts, and market information. Over the past decade, the hotline has expanded its features and enhanced information flow, significantly strengthening Ethiopia's agricultural extension system (ATI, 2022).

The 8028 FHL has been instrumental in supporting Ethiopia's Agricultural Commercialization Cluster (ACC) Program by improving access to timely and relevant agricultural information. Through the integration of digital advisory services into the extension system, the hotline has facilitated a Pluralistic Extension Approach (Intervention 1.10), enabling both public and private sector actors to participate in

knowledge dissemination. Additionally, by scaling up digital agricultural advisory services (Intervention 1.12), the platform has made agronomic guidance accessible to millions of farmers, enhancing the reach of Ethiopia's extension services. The 8028 FHL has also bolstered national capacities for pest and disease monitoring and early warning (Intervention 1.13), empowering farmers and Development Agents (DAs) to respond effectively to agricultural threats. Moreover, the hotline has played a crucial role in disseminating early warnings about wheat rust outbreaks (Intervention 2.14), allowing farmers to take preventive measures in a timely manner.

By bridging the gap between research institutions, policymakers, and farmers, the 8028 FHL has significantly contributed to agricultural commercialisation efforts in Ethiopia, improving smallholder productivity and strengthening value chain integration. The lessons learned from the implementation of the 8028 FHL offer valuable insights for scaling up digital agricultural advisory services across Africa and beyond, thereby fostering more effective agricultural development and commercialization strategies.

The objective of this report is to assess the role of the 8028 Farmer Hotline (FHL) in enhancing agricultural commercialisation in Ethiopia through digital advisory services. It evaluates the hotline's contribution to information access, extension services, smallholder productivity, and resilience to pests and diseases. The findings will provide information on how to improve digital advisory platforms and their integration with another platform to better support the Ethiopia's agricultural sector.

2. Materials and Methods

2.1. Geographic Scope

The 8028 Farmer Hotline's automated hotline module is accessible nationwide, while the remaining three modules helpdesk, alert, and survey systems were expanded to 300 Agricultural Commercialisation Cluster (ACC) woredas, supported by 600 agricultural experts. These modules focus on enhancing service delivery specifically in the ACC woredas, further improving digital agricultural advisory outreach.

2.2. Operational Design/Model

The hotline consists of four key modules tailored to address the diverse needs of Ethiopian smallholder farmers. The IVR-based Automated Hotline provides advisory services on 21 crop varieties (including cereals, pulses, oils, and vegetables), livestock value chains (such as dairy, fattening, improved household poultry, small-scale poultry, apiculture, and camel farming), basic financial literacy, and COVID-19 responses (Figure 1). These services are accessible in six Ethiopian languages: Amharic, Afaan Oromo, Tigrigna, Wolaytigna, Sidamigna, and Somali. Through this module, farmers can navigate a pre-recorded menu in their preferred language via a toll-free number. The IVR-based Helpdesk System allows farmers to submit inquiries and receive expert advice. The IVR and SMS-based Survey System enables real-time data collection for early detection of pests and diseases, while the IVR and SMS-based Alert System

broadcasts early warning messages about pests, diseases, and climate-related risks, including unseasonal rainfall.

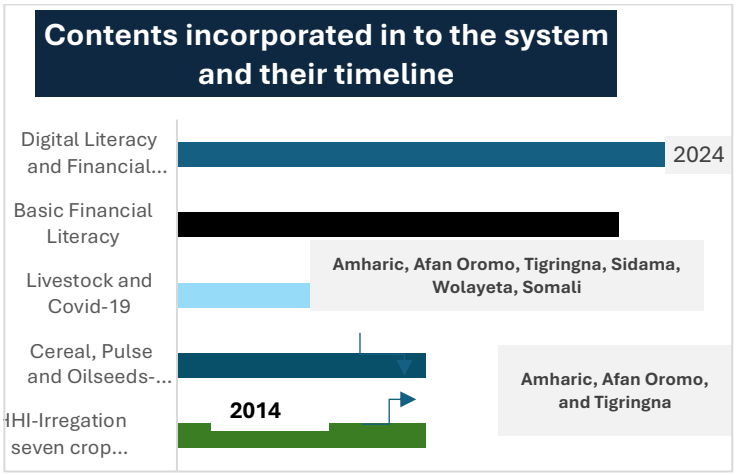

Figure 1. Contents Incorporated into the 8028 FHL.
Source: System design

2.3. Data Collection and Analysis

This review compiles insights from multiple sources, including hotline usage data, the ACC program (2019-2024) terminal report, focusing on the 8028 FHL project, and findings from the joint monitoring report. Both quantitative and qualitative data were analysed, incorporating user engagement metrics, system performance indicators, and feedback from farmers, extension agents, and policymakers. Data collection was primarily based on various sources, including quantitative data from the hotline's system dashboard (such as call metrics, access frequencies, and service usage patterns). Additional insights were gathered from the ACC program reports, the project's internal monitoring reports, and other relevant project document.

3. Results and Discussion

3.1. The role of 8028 Farmer Hotline in the ACC program

The 8028 Farmers' Hotline is a pivotal component of the ACC program, directly contributing to its goal of enhancing production and productivity among smallholder farmers in Ethiopia. As an integral part of the ACC program, the hotline enhances access to timely, relevant, and localized agricultural information, helping farmers improve productivity. It specifically focuses on strengthening access to inputs, extension services, and financial resources. By delivering reliable agronomic advice, pest and disease alerts, and financial literacy resources, the hotline significantly boosts the overall efficiency and productivity of smallholder farming operations ATI (2024).

Through its IVR-based system, the 8028 Farmers' Hotline enables farmers to interact with experts, access information in their local languages, and receive personalized guidance tailored to their agricultural needs. This addresses one of the major barriers to agricultural productivity—the lack of timely and accurate information. By offering real-time solutions to critical issues such as crop management, pest control, livestock care, and financial planning, the hotline supports better-informed decision-making, leading to more sustainable and productive farming practices. The hotline's integration within the broader ACC framework ensures that smallholder farmers in Ethiopia are equipped to enhance their agricultural output, which is a cornerstone of the program's success.

In addition to agricultural information, the 8028 Farmers' Hotline has also been instrumental in disseminating nutrition-sensitive agricultural content, significantly improving smallholder farmers' awareness of better dietary practices. This initiative supports the promotion of nutrition-sensitive agriculture practices while enhancing the engagement of women and youth in the sector. By incorporating nutrition and gender inclusion content and collaborating with organizations like Save the Children, the hotline has increased access to valuable nutrition information. This collaboration supports the adoption of healthier farming and consumption habits, ultimately contributing to improved nutrition outcomes for farming households

3.2. Key Project Results and Their Contribution to the ACC Program

The main objective of the project was to enhance agricultural productivity and income by improving farmers' access to digital extension services. This aligns with one of ATI's key performance indicators: increasing the percentage of farmers benefiting from digital advisory services. Below is the key project results achieved as part of the project result:

The hotline has successfully handled over 66.5 million calls since its inception, demonstrating the demand for digital extension services (Figure 2). In response to growing needs, additional extension packages on fisheries, aquaculture, forage production, banana, avocado, mango, soybean, irrigation wheat, sunflower, and field pea have been developed and are awaiting budget allocation for integration.

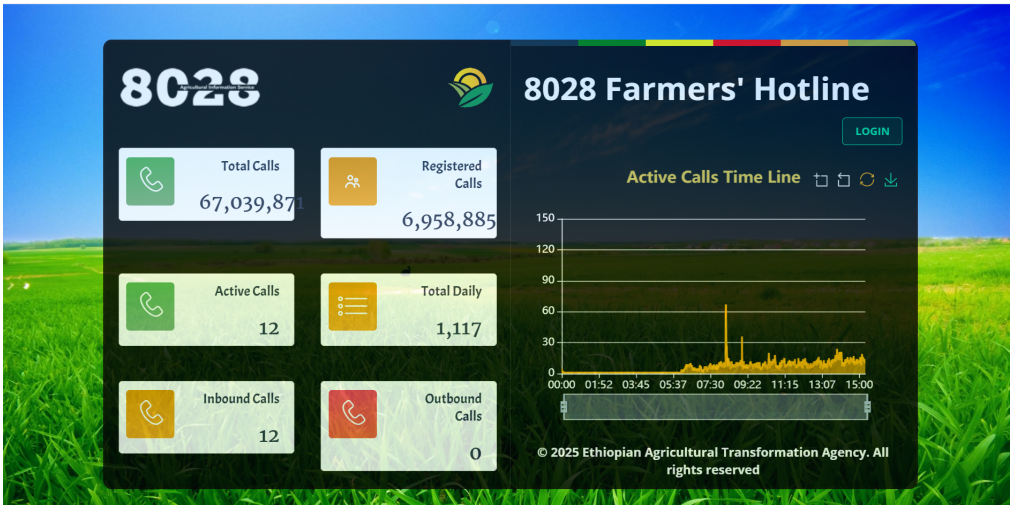

Figure 2. The Hotline Dashboard
Source: System dashboard

The 8028 Farmer's Hotline is recognized as the third-largest digital agricultural tool in Africa and the seventh largest in low- and middle-income countries, according to the "Status of Digital Agriculture in LMICS" report published by Beanstalk AgTech in 2023 (Figure 3). This positioning highlights the significant reach and impact of the hotline in enhancing agricultural productivity and commercialization, supporting millions of smallholder farmers across Ethiopia and similar regions. Its prominence underscores the crucial role of digital agriculture in transforming farming practices and resilience in low-resource settings.

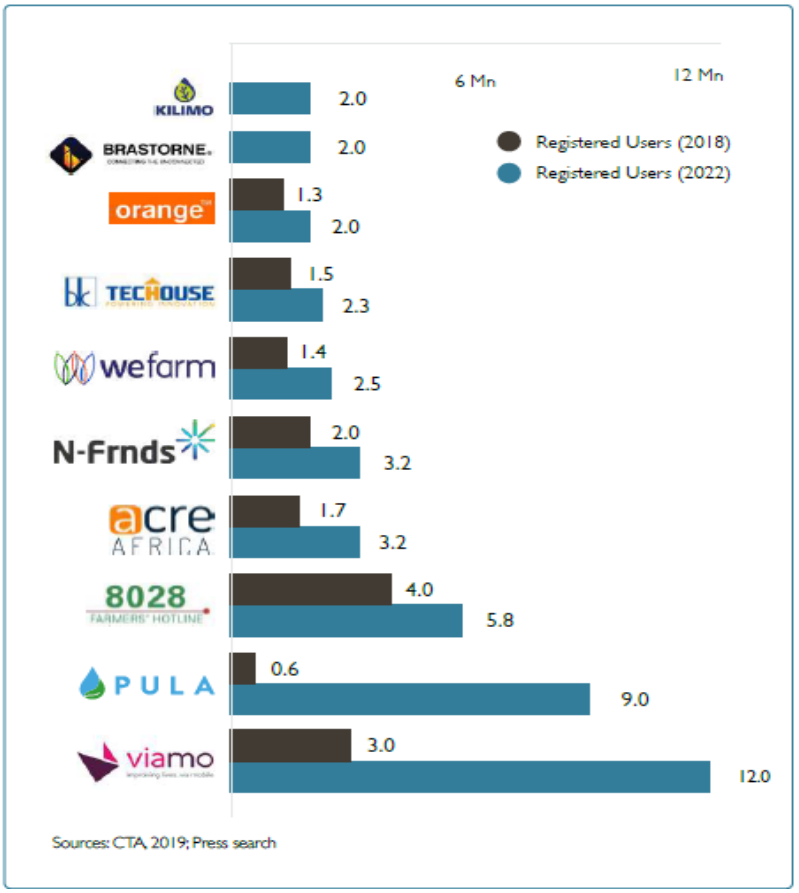

Figure 3: Registered Users of Top 10 D4Ag Solution Providers, SSA,
Source: Beanstalk AgTech. (2023). State of the Digital Agriculture Sector.

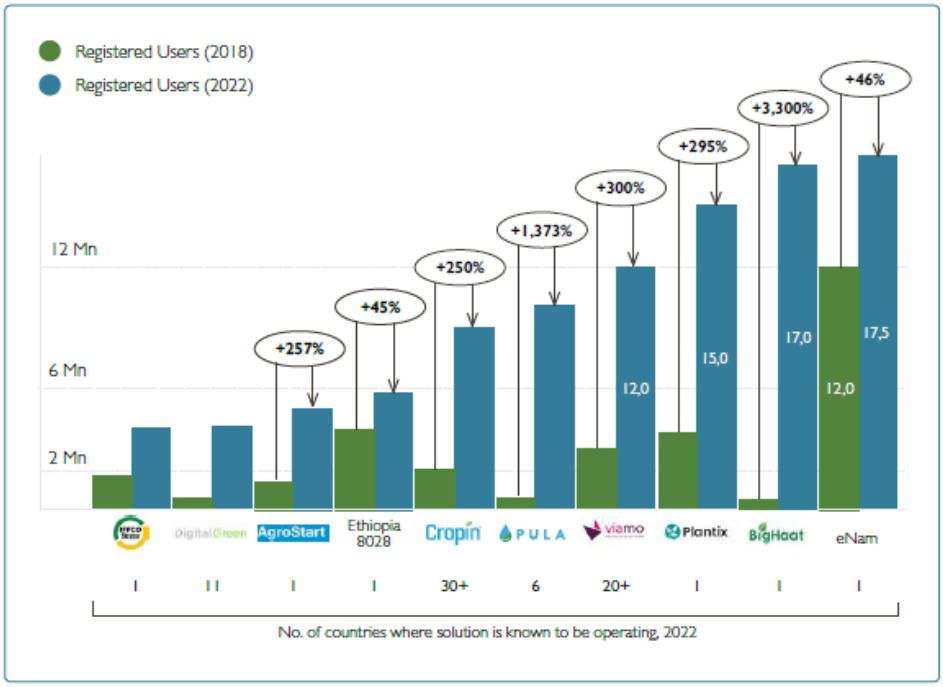

Figure 4. Registered Users of Top 10 D4Ag Solution Providers.
Source: Beanstalk AgTech. (2023). State of the Digital Agriculture Sector.

To date, the system has facilitated the submission of over 27,000 farmer queries, with more than 26,000 expert responses provided (Figure 5). This module has been instrumental in strengthening woreda-level advisory services, covering 300 woredas under the ACC. The system ensures that farmers' concerns—ranging from crop protection issues to soil fertility management—are addressed with context-specific and timely responses from agricultural experts.

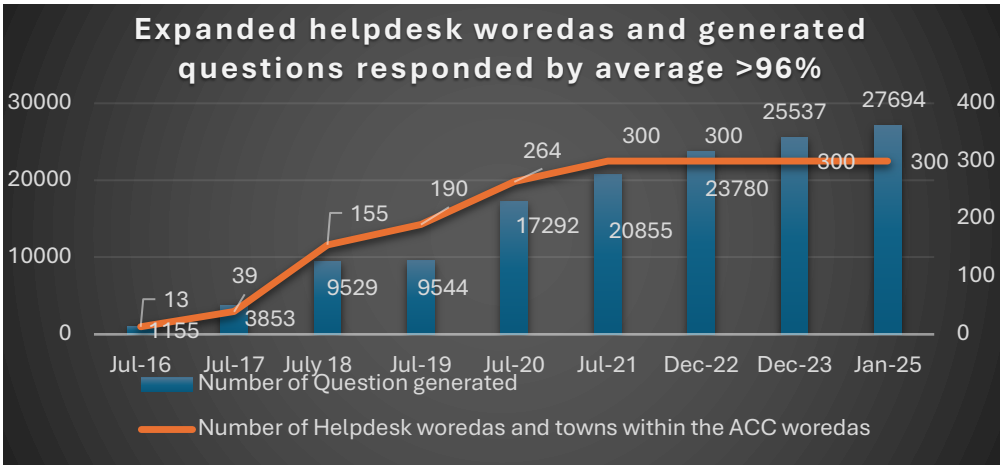

Figure 5. Number of generated questions with response progress and helpdesk woreda expansion.
Source: System dashboard

The IVR/SMS-based survey system plays a vital role in the rapid collection of field data, which significantly contributes to agricultural research and extension services. This module has been pivotal in identifying and managing major crop and livestock disease outbreaks, supporting timely decision-making. Since its integration in 2017, the system has conducted over 1.5 million surveys, primarily focusing on tracking threats such as wheat rust, fall armyworm, and desert locust infestations (Figure 6). The collected data is analysed to enhance predictive models, leveraging farmer reports combined with satellite imagery. This approach improves early warning systems, enabling better forecasting and management of agricultural risks. For example, International Maize and Wheat Improvement Centre (CIMMYT) has utilized this data to develop a system that delivers wheat rust predictions directly to farmers' phones, providing them with real-time warnings and tailored advice (Mottaleb *et al*., 2021). By sharing these insights with government institutions and local agricultural offices, the system ensures that interventions are timely and effectively address emerging threats. This collaborative effort exemplifies the power of digital technologies in improving agricultural resilience and decision-making, ultimately fostering more efficient and responsive agricultural systems.

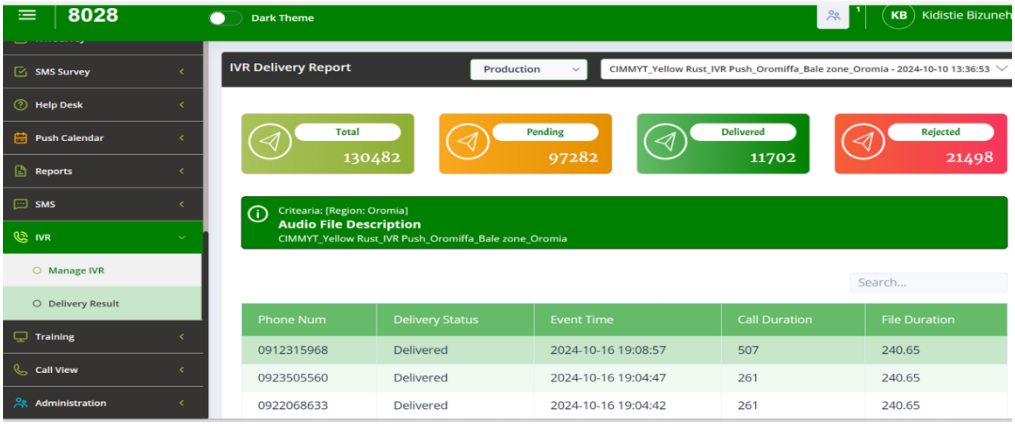

Figure 6. The IVR/SMS Survey System
Source: System dashboard

Since its launch, over 8.8 million alerts have been broadcasted, informing farmers about pest outbreaks, disease risks, climate-related shocks, and nutritional best practices. This module has been widely used in collaboration with Save the Children International, delivering nutrition-sensitive agricultural advisories aimed at improving food security and dietary diversity in rural Ethiopia. The targeted push-based messaging

system ensures that farmers receive timely and relevant updates, enabling them to make informed decisions.

3.2.1. Improved Adoption of Agronomic Practices

The 8028 Farmer Hotline, particularly through its automated hotline and helpdesk system, has been instrumental in improving the adoption of agronomic practices among smallholder farmers. By providing on-demand advisory services in six languages, the platform has bridged the gap between extension agents and farmers, ensuring year-round access to vital agronomic information. With over 66.5 million calls and 6.9 million registered users (2.78 million from ACC woredas), the hotline has shifted agricultural extension toward a digital approach, complementing traditional methods. This transition has contributed to better farm management practices, including the use of certified seeds and enhanced agricultural techniques, ultimately supporting higher productivity levels in line with the ACC program's objectives. Furthermore, the hotline has driven a 23% increase in farmers accessing extension services, with the number of beneficiaries rising from 2.12 million to 3.97 million. These results highlight the critical role of digital advisory services in boosting agricultural productivity and addressing smallholder farmers' needs, supporting the goals of the ACC program, and driving improvements in farm management and overall productivity ATI (2024).

3.2.2. Strengthened Pest and Disease Surveillance

The survey module has played a vital role in strengthening early pest and disease surveillance, contributing to the ACC's efforts in mitigating risks that threaten agricultural productivity. By deploying over 1.5 million surveys, the system has facilitated real-time monitoring and response to threats such as wheat rust, fall armyworm, and desert locust infestations. This has been further enhanced through collaborations with ATI, CIMMYT, EIAR, and MoA, leveraging digital tools and predictive analytics to ensure timely interventions. The early warning mechanisms have minimized potential yield losses, supporting ACC's goal of increasing smallholder resilience to biotic and abiotic stresses. The hotline's impact on productivity and profitability is evident, with farmers reporting better crop protection strategies 40%, planting techniques 20%, and post-harvest handling 20%. It has also helped optimize resource use, improving fertilizer application and irrigation decisions. The integration with other agricultural extension services, including development agents and Woreda experts, has strengthened its credibility and adoption. However, challenges such as limited mobile phone access, digital literacy, and infrastructure gaps must be addressed. Solutions like capacity-building, awareness campaigns, and infrastructure improvements will be key to enhancing the hotline's effectiveness and supporting sustainable agricultural commercialization (ATI, 2024).

3.2.3. Enhanced Farmer Access to Expert Advisory Services

The helpdesk module has improved the accessibility of expert advisory services, strengthening localized agricultural extension efforts. With over 27,000 queries

submitted and 26,000 responses provided, the system has enabled farmers to receive tailored agronomic guidance, aligning with ACC's emphasis on farmer-centred extension approaches. By ensuring rapid expert responses to farmer inquiries, the platform has reinforced knowledge-sharing and advisory services at the woreda and kebele levels, contributing to improved farm decision-making. According to the joint monitoring visit, the 8028 Farmers' Hotline has significantly contributed to agricultural commercialization by enhancing farmers' access to market-oriented advisory services. Most farmers (97%) use the hotline, with 90% actively engaging with its automated services. The IVR Helpdesk and SMS alert system have played a key role in delivering timely agronomic advice and facilitating two-way communication, allowing farmers to report crop diseases and pest outbreaks. By providing multilingual support and covering diverse agricultural topics, the hotline has bridged the gap between smallholder farmers and modern agricultural practices, driving improved decision-making in critical farming stages (ATI, 2024).

3.2.4. Timely Information Dissemination for Risk Management

The Interactive Voice Response/Short Message Service alert system has been pivotal in delivering crucial information on pest outbreaks, climate-induced risks, and best agronomic practices. With over 8.8 million alerts sent, it has provided farmers and extension agents with timely warnings, enabling proactive decision-making. This supports the ACC program's goal of integrating digital solutions to improve risk management and enhance productivity, particularly in response to climate variability and market dynamics. Joint monitoring visits have highlighted the hotline's positive impact on productivity and profitability, with farmers reporting improvements in crop protection strategies (40%), planting techniques (20%), and post-harvest handling (20%). The system has also optimized resource use, such as improving fertilizer application and irrigation decisions. Its integration with other agricultural extension services, including development agents and Woreda experts, has bolstered its credibility and adoption. However, challenges like limited mobile phone access, digital literacy, and infrastructure gaps persist. Addressing these issues through capacity-building, awareness campaigns, and infrastructure improvements will be crucial in enhancing the hotline's effectiveness and supporting sustainable agricultural commercialization (ATI, 2024).

3.2.5. Capacity Building and Stakeholder Engagement

Beyond technological advancements, the 8028 Farmers' Hotline has contributed to capacity building by training (DAs, subject matter specialists, and agricultural extension experts. This has ensured that digital advisory services are effectively integrated into extension programs at all levels. Additionally, promotional materials have been developed and disseminated to enhance the visibility and accessibility of the platform, reinforcing ACC's broader objective of institutionalizing farmer support mechanisms.

In general, the 8028 Farmers' Hotline has played a pivotal role in Ethiopia's agricultural commercialization by improving farmers' access to timely and reliable advisory services. Through its core modules—Automated Hotline, IVR Helpdesk, IVR/SMS-based Survey System, and IVR/SMS-based Push System—it has empowered millions of farmers with critical agricultural information, boosting productivity and market linkages. These services have enhanced decision-making, facilitated real-time data collection, and supported policy responsiveness, all while fostering the adoption of best practices. By integrating digital advisory systems, the 8028 Farmers' Hotline has contributed significantly to bridging the gap between traditional farming and modern agribusiness, supporting a more productive, resilient, and market-connected agricultural sector in Ethiopia.

3.3. Role of the 8028 Farmers' Hotline in the Development of Digital Agriculture Roadmaps

The success of the 8028 Farmers' Hotline has been crucial in shaping Ethiopia's Digital Agriculture Extension and Advisory Service (DAEAS) 2030 Roadmap and Digital Agriculture Roadmap (DAR). The lessons learned from the hotline have informed strategies for expanding digital advisory services, integrating them with traditional methods for better efficiency and engagement. Its impact has highlighted the need for personalized, localized advisory services, with the integration of biometric data collection enhancing service delivery. The 8028 Hotline's success has also influenced the development of digital tools for market linkages, supply chain management, and financial services, which are key elements of the DAR and DAEAS. By institutionalizing digital advisory models, Ethiopia is advancing agricultural commercialization, supporting innovations like AI-powered advisory systems, digital market platforms, e-vouchers, and precision agriculture. These efforts position Ethiopia to accelerate its digital agriculture transformation, increasing productivity and market access for farmers.

3.4. Key Challenges and the Way Forward

Despite the significant success of the 8028 Farmer Hotline, several challenges have emerged that impact its effectiveness and sustainability. One major challenge is the accuracy of self-reported farmer data, which affects the quality of advisory services. Since the hotline relies on self-reported user profile information, there is a risk of inaccuracies, leading to generalized recommendations rather than precise, location-specific advice. Addressing this issue requires accelerating the farmer profiling process in alignment with the National ID program and cleaning existing farmer records within the system. Another critical issue is the complexity of updating and approving advisory messages. The involvement of multiple researchers and experts from various institutions often leads to delays in content updates, reducing the timeliness of extension messages. Streamlining the content approval process and enhancing stakeholder coordination would ensure that farmers receive relevant and up-to-date

agricultural advisories. Additionally, low literacy levels in rural areas pose a barrier to effective engagement with the hotline. Providing multilingual, simplified, and audio-based content can improve accessibility and comprehension for farmers with limited literacy skills.

Sustaining long-term user engagement is another challenge, as farmers may lose interest over time. To maintain engagement, the hotline can implement ongoing outreach campaigns, leverage community leaders and farmer organizations, and introduce incentives for repeat users. Regular updates on agricultural practices, market prices, and weather forecasts will also help sustain interest. Lastly, limited access to digital devices remains a concern, as some farmers lack even basic feature phones, restricting their ability to use the service. This challenge could be addressed by forming partnerships with stakeholders to improve access to affordable digital tools or introducing community-based solutions that enable shared access. By tackling these challenges through strategic interventions, the 8028 Farmer Hotline can further enhance its impact and continue to serve as a valuable tool for agricultural transformation in Ethiopia.

3.5. Lessons Learned

The implementation of the 8028 Farmer Hotline has provided valuable insights into the future of digital agricultural advisory services. One of the key lessons learned is the importance of multi-stakeholder collaboration. The successful partnership between ATI, MoA, EIAR, Ethio Telecom, and various international organizations such as Digital Green, CIMMYT, Precision Development, Mercy Corps Ethiopia and Mercy Corps AgriFin Program have been crucial in scaling and sustaining the hotline. These collaborations have ensured that the service remains relevant and responsive to farmers' evolving needs. Strengthening partnerships between public institutions, the private sector, and development partners will be critical for sustaining and expanding digital agricultural advisory services. Another major lesson is the need for efficient content updates to support agricultural commercialization. The hotline's role in the ACC program has highlighted how delays in content generation and approval can limit the effectiveness of advisory services. To maximize its impact, future efforts should focus on improving coordination among stakeholders and streamlining content updates to ensure that farmers receive real-time, relevant advisory message.

Another critical takeaway is the advantage of leveraging existing government structures at the woreda level. The hotline benefits from the presence of local agricultural experts who provide support through the helpdesk system. Strengthening these networks will enhance accessibility and effectiveness, particularly for marginalized farmer groups. Additionally, the retention of skilled experts and knowledge transfer remains a significant challenge. The sustainability of the 8028 Farmer Hotline depends on ensuring that technical expertise is maintained and continuously developed. Investing in career development opportunities and fostering collaborations with academic institutions and private sector professionals can help retain the expertise needed for

long-term success. These lessons collectively highlight the importance of strong partnerships, efficient content management, localized support systems, and sustainable human resource strategies in shaping the future of digital agricultural advisory services in Ethiopia.

4. Conclusion and Recommendations

The 8028 Farmers' Hotline (FHL) has played a pivotal role in advancing Ethiopia's Agricultural Commercialization Cluster (ACC) Program and in strengthening the country's digital agriculture ecosystem. By improving timely access to critical agricultural information, particularly during disease outbreaks and climate-related shocks, the hotline has enhanced farmers' decision-making and responsiveness to production and market challenges. Through its multi-channel digital advisory services—leveraging IVR, SMS, and data-driven feedback mechanisms—the platform has delivered essential agronomic and climate-smart recommendations to millions of farmers, including those in remote and underserved areas.

Beyond service delivery, the 8028 FHL has served as a unifying platform that brings together key government institutions, development partners, research organizations, and private-sector actors to collaboratively advance digital agricultural transformation. Its implementation experience and evidence base have directly informed national policy and strategic frameworks, notably contributing to the Digital Agriculture Extension and Advisory Services (DAEAS) 2030 Roadmap and the Digital Agriculture Roadmap (DAR). The hotline has also laid the groundwork for complementary digital systems, including the National Market Information System (NMIS), which now covers hundreds of markets nationwide, and the national farmer profiling initiative linked to the National ID system.

While challenges remain—particularly related to digital literacy, infrastructure gaps, and sustained user engagement—the lessons and institutional partnerships established through the 8028 FHL provide a strong foundation for scaling more integrated, intelligent, and sustainable digital advisory services. As such, the hotline stands not only as a successful innovation but also as a cornerstone for Ethiopia's ongoing agricultural transformation and digital modernization agenda.

To ensure the long-term sustainability, scalability, and strategic relevance of the 8028 Farmers' Hotline, a forward-looking approach is required—one that strengthens its role as a national digital public good for agriculture and commercialization.

Develop a Centralized, Intelligent Digital Agriculture Knowledge System: A unified digital agriculture knowledge hub should be established to deliver personalized, multilingual, and data-driven advisory services to farmers, extension agents, and agribusinesses. This system should integrate diverse datasets—such as weather, soil, agronomy, market, and financial information—and leverage artificial intelligence for predictive and prescriptive analytics. Multi-channel dissemination through IVR, SMS,

chatbots, mobile applications, and emerging platforms should be maintained to ensure inclusivity and accessibility.

Advance Digital Capability and Advisory Efficiency: Targeted investments in digital literacy are essential to improve farmer and extension-worker engagement with digital tools, particularly in rural and pastoral areas. Community-based training, awareness campaigns, and extension-led digital coaching can significantly reduce adoption barriers. At the same time, expanding AI-driven and personalized advisory services—supported by improved farmer profiling and integration with the National ID system—will enable more precise targeting, relevance, and impact. Streamlining content development and approval processes will further ensure timely, localized, and context-specific recommendations.

Institutionalize Digital Advisory Services within the Ministry of Agriculture: For long-term sustainability, digital advisory services should be formally institutionalized within the Ministry of Agriculture (MoA) as core components of the national extension system. This includes establishing MoA-owned call centers that strengthen the 8028 Farmers' Hotline as an official digital extension channel. Embedding the platform within MoA's operational, financial, and human resource structures—while continuing technical and strategic support from ATI and development partners—will ensure continuity, national ownership, and alignment with Ethiopia's broader agricultural transformation goals.

Collectively, these actions will enhance the 8028 Farmers' Hotline's contribution to agricultural productivity, commercialization, and system-wide digital transformation, positioning it as a sustainable and scalable backbone of Ethiopia's modern agricultural extension system.

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The Role of Agri hub in Enhancing Business Skills and Access to Finance for Agricultural Small and Medium Enterprises

Solomon Legesse*, Shimelis Altaye, Beshana Tesso, Alemnew Abaye, Henok Mesfin, Yordanos Gebreleul, Leake Gebreselama, Mulugeta Mohammed, Yonatan Gedamu, Yonas Tadesse, Wolde Wakaso, Fufa Olbaha, Dagnachew Lule

Agricultural Commercialization Cluster (ACC) Vertical, Ethiopian Agricultural Transformation Institute (ATI), P.O. Box 708, Addis Ababa, Ethiopia
Corresponding Author email: Solomon.legesse@ati.gov.et

Abstract

The agribusinesses along the value chains of Small and Medium Enterprises (SMEs) remain largely underdeveloped due to lack of entrepreneurial innovation, business knowledge and skills, business networking, access to adequate finance, and market linkages. This situation demanded targeted support for these SMEs, as they are major catalysts to improve production, food security, and the rural economy. ATI has designed and implemented the Agri Hub project to improve business development capacities and access to finance and targeted 1340 SMEs found in Oromia, Amhara, former SNNP, and Tigray regions. The project provided business development support for targeted SMEs through a 4-tiered Business Development Service (BDS). Thus far, the project has provided BDS support for 12 categories of 1,239 SMEs in which the input was related, and livestock enterprises shared the bigger (27%) and the lower (1.4%) share of BDS support, respectively. Most SMEs (38%) are found at center of conception BDS tier, and a smaller proportion (11%) are at the accelerator tier of BDS. Business skill development training was provided for 2,092 (26% female) owners and staff of 1,239 SMEs. The BDS support provided, and the results achieved so far suggest that any types of agribusinesses operating along the value chain need to be supported with customized business development services and access to finance to grow, scale, sustain, and deliver competitive products and services to smallholder farmers.

Keywords: Agribusiness, Entrepreneurial innovation, Market linkages

1. Introduction

Small and Medium scale Enterprises (SMEs) are regarded as the engine of economic growth and equitable development in developing economies. They are recognized as an integral component of economic development and a crucial element in the effort to lift countries out of small-scale businesses. They are a driving force for economic growth, job creation, and poverty reduction in developing countries. In most African countries, SMEs account for a significant share of production and employment and are therefore directly influencing poverty alleviation (Agyapong, 2010).

In Ethiopia, the SMEs sector is the second largest employment-generating sector following agriculture. The sector contributes 3.4% of the GDP, 33% of the industrial

sector's contribution. This evidence confirms that although a focus on broad-based growth and transformation through the promotion of MSEs has been underscored in various development plans, both the level of unemployment and quality of jobs remain a concern in Ethiopia. MSEs have been performing below capacity, and their growth has been severely constrained by various factors (Gebreyesus, 2007[4]). The MSE development was the primary focus of the Growth and Transformation (GTP II) of the country to expand employment and reducing poverty, mainly women and youths (NPC, 2016). The government of Ethiopia proposed MSEs as means of creating employment to millions of youths and achieving sustainable development goals.

Along the agricultural value chain, agriculture-oriented enterprises play critical roles in developing infrastructure, producing & distributing inputs, processing, marketing, retailing, and exporting. SMEs are known for their greater utilization of local raw materials, employment generation, taking part in rural and urban development, promotion of entrepreneurship, mobilization of local savings, linkages with bigger industries, and provision of regional balance by spreading investments more evenly. They also provide avenue for self-employment and opportunities for training managers and semi-skilled workers (Taiwo *et al.,* 2012).

Given the role and the attention, they took, the performance of SMEs in Ethiopia has not been satisfactory. Several challenges have contributed to the absence of a sufficient number of agriculture enterprises and underdeveloped operations. These include lack of business skills, limited access to appropriate financial resources, weak market links, lack of entrepreneurial innovation, and inefficient supply chains. Almost half of microenterprises, 40% of small firms, and 18.5% of medium firms in Ethiopia reported that access to finance is the major constraint to their daily operations (World Bank, 2016). The study conducted by ATI further identified key challenges, including lack of credits/loans for investment and working capitals, lack of business development skills and linkages, inadequate business development services, lack of financial management skills, and limited access to training and mentorship programs.

Taking in to account the role of agricultural SMEs in transforming the Ethiopian agriculture, the Ethiopian Agriculture Transformation Institute (ATI) has engaged in establishing and supporting Agri SMEs since its establishment in 2010. Within ATI's larger mandate, there are many projects that are involved with private sector or cooperative based enterprises in the agricultural sector. These include Agricultural One-Stop Shop Center (AOSS), Mechanization Service Centers (MSC), Cooperative Based Seed Producers (CBSP), Integrated Shallow Ground Water Irrigation Development (ISGWID), Direct Seed Marketing (DSM) and Direct Input Marketing (DIM).

[4] Gebreyesus, M. 2007. Growth of microenterprises. Empirical Evidence from Ethiopia.

Thus, there is a need for targeted support to these agricultural enterprises, as they are catalysts to improve production, food security, and rural incomes; and are building blocks to form larger agricultural enterprises spurring Ethiopia's future economic growth. To this end, ATI designed a project called Agri-Hub with the main objective of promoting the development of the private sector in agriculture to improve livelihoods and economic opportunities. The project has been implemented to contribute to sustainable growth and impact of Agri-SMEs operating in agricultural value chains through business skills enhancement and access to finance. This paper presents the key contribution of and lessons from the Agri-Hub project in supporting SMEs to be competent in the market.

2. Materials and Methods

2.1. Description of targets and implementation areas

The Agri-hub project targets are Agri-SMEs established and supported by other ATI projects operating in ACC woredas that are selected based on their potential for commercial growth, social impact and their relevance to the value chain they are supporting. The number of SMEs targeted for the project period was 1340 Agri-SMEs. Although priority has been given to target SMEs established under various ATI projects, there has been room created during the implementation time to identify and consider other SMEs already operating along the value chains. These include the exporter SMEs, value addition SMEs, farmers production clusters (FPCs) and others. In terms of SME types, the project targeted more than 12 types of SMEs, including AOSS, DIM/DSM, MSC, MSP, CBSP, FPC, HSGA, ISGWID, Livestock enterprises, agro-processors and export-oriented SMEs. The target SMEs are found in Oromia, Amhara, Tigray, Sidama, Southwest, Central Ethiopia, and South Ethiopia regions.

2.2. Modalities used to deliver BDS for Agri-SMEs

The Agri Hub project provides support to SMEs based on their scale, maturity and needs, through a 4-tiered BDS model. As figure 1 illustrated, these BDS tiers are named as Center of Conception, Center of Excellencies, Capacity Booster and Accelerator Tiers. The Centre of Conception is BDS tier of the project for providing mainly basic business training and business model diagnosis to a large pool of enterprises, groups and other newly established Agri-SMEs that are under ATI support but not legally registered yet. Agri-SMEs under the Centre of Excellency of the BDS tier are Agri enterprises that have consistent business throughout the year and Canter of Excellencies identified for standardization and shared BDS. The Capability Booster and Accelerator BDS tiers are the higher tier of support for enterprises that are slightly larger and in a more progressive stage of their business lifecycle. Agri-SMEs at Capability Booster level is selected from the centre of excellency pool based on criteria tailored to the specific MSME type and they are provided with fuller suite of BDS. SMEs at the Accelerator BDS tier are high-potential enterprises selected through stringent evaluation methods. These enterprises are provided with deep customized BDS that include customized business advisory and a one-to-one mentoring service.

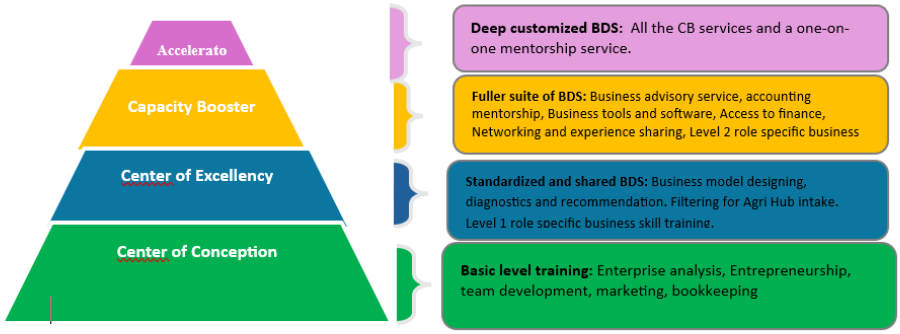

Figure 1. Level of enterprise maturity and types of BDS for each level of enterprise maturity

2.3. Methods and tools used for engagement of SMEs

Agri-Hub used different techniques and tools to engage SMEs in the project, doing business model diagnosis and conducting enterprise graduation. This section describes the techniques and tools used.

Agri-hub Intake: The project used criteria to select and engage Agri-SMEs to the project. The main criteria used for Agri-hub Intake are the presence of clear enterprise structure and required staff, defined business model, stationed at specified working place, operational the whole year, and generate revenue from regular business activities.

Business Model Diagnosis: A business diagnostic assessment is conducted using multiple tools available to get a comprehensive picture of the SMEs' operations, including financial performance, customer service, marketing insights, and other vital components.

Enterprise Graduation: Pre-diligence and due-diligence criteria are also used to identify the enterprises qualifying to graduate from capacity booster tier to accelerator tier. Pre-diligence assessments are conducted through desk reviews of documents of SMEs applying to enter the accelerator tier. The criteria used to conduct this assessment are the SMEs' motivation, experience, development, revenue growth, staff size, financial statement and talent. The due-diligence assessments are conducted mainly through in-person visits and assessments of the SMEs using the pre-diligence process. In this assessment the criteria used are SMEs' performance in marketing, operation, financial management, business strategy, supply chain and human capital.

2.4. Project constituents

Agri-Hub is implemented through its three focus areas. These are Business skills development support for Agri-SMEs, Access to finance for Agri-SMEs, Development of sustainable Agri Hub business model for further outreach and scaling up of the approach. The Agri-Hub project activities have been implemented since 2020, and major activities implemented in each of the three focus areas are highlighted below.

2.4.1. Business skill development

Business skill development undertakes the major BDS for targeted Agri-SMEs. Its purpose is to institutionally strengthen target SMEs to deliver competitive products or services through various methodologies adapted to their size and needs. Major business skill development activities implemented to capacitate and strengthen target SMEs include business diagnosis and training need assessments, business skill development training delivery to the SMEs owners and staff, provision of accounting mentorship and accounting software, conducting group networking and experience sharing workshops, and business advisory service provision.

2.4.2. 2Access to finance

For BDS to succeed, it needs to have activities that facilitate access to finance that meet affordability, timelines and adequacy. Agri Hub has implemented various activities to improve the financing gap of SMEs that have attributed both the demand side and supply side. The demand-side activities of the project were to do more on the characteristics of enterprises that limit their ability to fulfill the criteria for bank loans leading to financial limitations. The supply-side activities of the project were more related to the financial institutions. Hence, activities listed below are designed and implemented under component II of the project to improve Agri-SMEs' bankability and facilitate the linkage of mature enterprises to financial institutions such as commercial banks, microfinance institutions (MFI) and investment funds for working capital and asset finance to ensure sustained business growth.

- Establishing partnership with Financial Institutions to ensure adapted financial services delivered to Agri SMEs
- Facilitating financial linkage workshops /trainings
- Conducting Financial need assessment of SMEs
- Provision of comprehensive technical support to SMEs to make them bankable for access to finance.

2.4.3. Development of sustainable Agri-Hub business model

Agri-hub has also included activities to sustain the outreach of the project after the project lifetime. The objective was to develop efficient methodologies and tools and network of partners and service providers to build on for further outreach post Agri Hub. Accordingly, activities implemented to achieve this project component objective include:

- Assessment of methodologies and tools already developed by ATI for BDS support to SMEs.
- Creating partnership with partners for standardization of BDS tools.
- Implementation support to ATI and service providers to improve methodologies, tools and organization for BDS support to Agri-SMEs.
- Capacity building of BDS service providers.
- Website creation and updating.
- Stakeholder workshops to communicate and exchange on results achieved.

3. Results and Discussion

Through the partnership, with the Agri-Hub project a total of 361 SMEs has increased their turnover by at least 20%, and the number of indirect beneficiary smallholder farmers has reached 7.7 million. In addition, the project has contributed for jobs creation of 3,584 individuals through supporting target Agri-SMEs. Compared to the project target values, 82%, 100% and 90% of the target values achieved for turnover, indirect beneficiary SHF and job creations, respectively. Major output level results of the project are highlighted below.

3.1. Business development skills support for SMEs

Over the course of the project, Agri-hub has provided business skills capacity building to 12 different categories of Agri-SMEs. In addition, business skill development support was provided for SMEs through the project four tiers of services based on enterprise scale, maturity and needs: Center of conception, Center of Excellence, Capacity Booster, and Accelerator. Initially the project developed and used the three-tier service, but following a review conducted during the mid of implementation period, it requires adding one more BDS tier to accommodate more SMEs that are beyond the criteria set in existing three BDS tiers. The distribution SMEs received in the BDs service are 474, 322, 313 and 130 SMEs across Conception (basic), competency (Level I), Capacity booster (level II) and Accelerator (Level III) tiers, respectively. The majority (38%) of the SMEs received support at the conception BDS tier. This is because most FPCs have not yet licensed.

Based on the Agri-SME types and BDS tier service arrangements, the project has provided business skill development support for a total of 1n239 Agri-SMEs. Table 1 presents the number of SMEs received business skill development per category. Large number of SMEs received the business skills drawn from AOSS/FSC (328) and FPC (333). However, small number of participants recorded livestock enterprises, which share only 1.4%. Considering the distribution of SMEs across regions, a total of 512 SMEs received business skills development from Oromia region, followed by Amhara region (323).

Table 1. Number of SMEs that received business skill development support by SME type and region.

Category of SMEs	Region				Total
	Oromia	Amhara	Former SNNPR	Tigray	
AOSS/FSC	161	65	89	13	328
DIM/DSM	4	3	6	8	21
CBSP	69	3	5	12	89
PSP	3	26	16	0	45
MSC	4	4	2	0	10
MSP	23	13	17	0	53
FPC	114	108	111	0	333
ISGWID	15	4	2	2	23
HSGA	8	7	20	0	35
Livestock enterprises	16	0	2	0	18
Cooperatives	60	59	5	66	190
VC - Processors & Exporters	35	31	23	5	94
Total	**512**	**323**	**298**	**106**	**1,239**

3.1.1. Training need assessment and business model diagnostics

To provide business development support, Agri-SMEs' business gaps and challenges have to be identified for improvement. Hence, since the project inception, training need assessments and business diagnostics of SMEs have been conducted for the sake of developing a more customized and specific business development training and advisory service. The assessments are conducted annually in a regular manner by the Agri Hub staff as well as by hired BDS service providers. Interview surveys, focus group discussions and workshops have been employed to conduct SMEs training need assessment and business model diagnostics.

To this end, the project has conducted six rounds of training need assessment and business model diagnostics across the four regions through the participation of a total of 345 (30 female) staff and owners from 301 Agri-SMEs. The assessments addressed all categories of SMEs. The training need areas were identified, and customized business development skill training modules were developed for target SMEs.

The most common business-related problems and skill gaps identified by the need assessments include:

- Inadequate business management, inventory management, financial accounting and recording practices among SMEs.
- Lack of conducting detailed market research including demand assessment and forecasts, lack of conducting regular customer satisfaction survey.
- Access to finance.
- SMEs' staff turnover.
- Linkage with customers and suppliers, suppliers' identification, and maintaining and sustaining linkages with suppliers and customers.

3.1.2. Customized and role specific business skill development trainings delivery for SMEs

Provision of business skill training is one of the major BDS services of the Agri-Hub project. As Figure 3 depicts, the project has provided role-specific business skill development trainings for 2,092 (26% female) owners and staff of 1,239 SMEs. The number of trained SMEs, individual participants, women participants and Agri-SME types has increased over time. The training courses were prepared based on the four BDS tiers of the project and topics covered are role-specific business skill development that includes business model and business planning, business management, accounting & finance, sales & marketing, communication, and leadership.

The post training assessments of the BDS courses are conducted each year following the training to determine whether the perceived skill change with SMEs owners and staff and the mean score of each training section was found to be at the level of expectation. The post-training assessment aims to ensure participants have acquired the necessary skills, knowledge and attitudes to perform their job roles successfully.

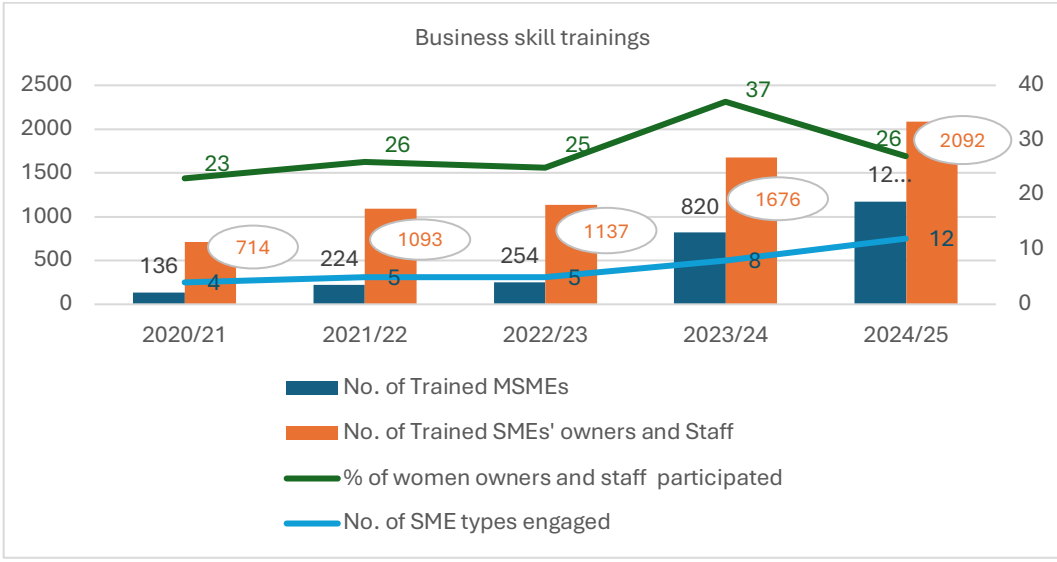

Figure 2. Summary of business skill training delivered

3.1.3. SMEs outfitted with business tools and accounting software

With the objective of improving operational efficiency, accuracy and strategic business decisions, the project has provided accounting software training for Agri-SME owners and staff. Accordingly, the project has provided financial and inventory management and customer relationship management training using Sage 50 accounting software for 194 Agri-SMEs by organizing eight training sessions. The total of number of training participants is 298 participants, of which 38% are women (Table 2). In addition, the

accounting software was installed for 179 trained SMEs, and SMEs were supported with mentoring and coaching sessions.

Table 2. Summary on Sage 50 accounting software training

Indicator	2021/22	2022/23	2023/24	2024/25	Total
No. of trained Agri-SMEs	53	67	71	13	194
No. of SME staff (Accountants) trained	85	88	99	26	298
% of women participated at Sage 50 accounting software training	28	35	39	12	114
No. of SMEs deployed /outfitted with sage 50 accounting software	46	57	66	10	179
Net Promoter Score (NPS) values of Sage 50 trainings (Average)	90%	83%	86%	88%	87%

3.1.4. Business advisory services

The Agri-Hub project has provided business advisory services (BAS) through both contracted BDS provider and Agri-Hub regional business mentor advisors for Agri-SMEs in Capacity Booster and Accelerator tiers. In total, the business advisory service engaged 524 SMEs in Level II (Capacity booster) and level III (Accelerator) categories in Oromia (216 SMEs), Amhara (110 SMEs), SNNP (183 SMEs), and Tigray (15 SMEs) regions. Targeting AOSS, CBSP, input supply, seedling nurseries, and related agribusinesses, the coaching employed on-site visits, one-on-one sessions, group workshops, and virtual support via Telegram and phone calls. The BAS services include business management and marketing, accounting and financial management, identification of suppliers, and linkage with other similar businesses. Despite challenges, security and logistical, the advisory service delivered significant results. Advisory service was provided for185 business plans (50–70% bankable), over 189 growth plans, more than 81 SWOT analyses, and widespread adoption of financial tools like cashbooks and sales ledgers.

3.1.5. Networking/Experience sharing workshops

The value of networking events for SMEs is indispensable, and it is more than merely expanding contact. Such events encourage best practice sharing, forge partnerships, and often trigger collaborations to uplift business results, increase division of labour and specialization, and increase access to markets, which require resources beyond the scope of individual SME operators. Thus, the AgriHub project organized several workshops to promote networking and experience sharing for enterprises. 28 networking and experience sharing workshops were conducted at federal and regional

levels. A total of 1,888 (10% female) business owners and staff of 370 SMEs have participated in the workshops. These workshops have helped SMEs' owners to identify opportunities & prospects, common challenges & potential solutions, major policy issues, and supports for business. Business planning, sourcing and distributing inputs, inventory management, sourcing and managing finance, auditing, staff management, customer handling, interaction with stakeholders, and business partners were among the topics covered during the group networking/experience sharing and B2B consultation workshops.

3.1.6. Business diagnostics and study to select value chains for support

Each year of project implementation, SMEs' business diagnostics were conducted for six types of Agri-Hub supported SMEs. Various documents and information sources were utilized for business diagnostics, which was followed by report preparation through outlining the key findings, recommendations, and proposed implementation strategies.

SME due diligence for graduating was the other major activity that has been conducted for SMEs in the Capacity Booster to Accelerator tier. The Agri-Hub project team has conducted due diligence to select SMEs having the potential to graduate and graduated qualified SMEs from the Capacity Booster to the Accelerator tier. In addition, a study to select value chains for Agri-Hub support to exporters and value-added SMEs was conducted. The findings of this study showed that the value chains are found relevant for support of exporters and Value addition SMEs, mainly for wheat, avocado, mango, and tomato. Based on this, the project has identified 27 value-added and exporting SMEs for Agri-Hub assistance.

3.2. Access to finance for SMEs

3.2.1. Provision of comprehensive support

Agri-Hub has provided comprehensive support to Agri-SMEs through the provision of tailored BDS to address constraints and make SMEs more bankable. BDS services provided include business management training, business plan development, marketing strategy, human resource management, financial systems, and bookkeeping. It also included tailored coaching and mentoring support depending on the needs and the capacity of the SMEs.

3.2.2. Access to finance workshops

Agri-Hub uses access to finance workshops as one of the important activities to enhance SMEs' access to finance. Three national and five regional access to finance workshops were organized and facilitated by the project (Table 3). The access to finance workshops were conducted at national and regional levels to share experiences of financial institutions in financing SMEs, communicate on the activities and results of

the project towards access to finance, and ensure synergies of the access to finance activities with other interventions of the project.

Table 3. Summary of access to finance workshops conducted during the project period

Workshop topic	Number of workshops	Number of participants Agri-SMEs	Number of participant FI	Collaborators
National forum on Access to finance	1	60	21	NBE, MoA & ATI-AgriHub
Access to finance project launching workshop	1	45	25	ATI- AgriHub
National forum on role of MFIs in financing Agriculture and Agri-SMEs	1	30	40	AEMFI, ATI-Agri-Hub
Regional access to finance linkage workshops	5	130	15	ATI - Regional offices
Total	**8**	**265**	**101**	

Major outcomes of access to finance workshops include:

- Enhanced networking of financial institutions with SMEs
- Banks presented their products and services to offer financing for Agri SMEs
- Created an awareness and understanding of the Bankability criteria of financial institutions.
- Reached consensus for the mutual benefit of banks and Agri-SMEs.
- Explored best experiences and available windows from Financial Institutions towards providing financial services to the SMEs
- Obtained recommendations for government priorities and policies related to financing Agri-SMEs

- Provided insight into future strategies and interventions by stakeholders to enhance access to finance for Agri SMEs

3.2.3. Partnerships with Financial Institutions

Accessing finance for SMEs through establishing partnerships with financial institutions was among the various efforts of the Agri-Hub project addressed. In connection with this, the project has aimed to create a partnership with 3 to 5 high potential commercial and public banks and facilitated several rounds of tripartite discussions among ATI, the donor, commercial and development banks to facilitate financing for AOSS and CBSP enterprises through AFD guarantee scheme arrangements. However, the guarantee scheme couldn't succeed due to a lack of interest in the banks to work with the AFD guarantee scheme modality. However, efforts are still continuing with some banks to collaborate with ATI in financing SMEs. Thus, the project has conducted engagement and signed MoU with 3 banks, namely, Cooperative Bank of Oromia, Abay Bank, and Awash Bank.

The comprehensive support of the project was rendered to SMEs and the partnerships created helped 128 SMEs to access finance from different financial institutions, including Abay bank, Cooperative bank of Oromia, Awash bank, CBE, and others. Out of these, 57 SMEs have received 366 million ETB loan from Abay bank. More than 83% of loans were collateral based on the loans period between 1-3 years. In 2023/24, additional 47 SMEs have also received a loan amount of 1.98 billion ETB from financial institutions. The SMEs getting the loan are composed of AOSS, MSC and CBSPs operating in Oromia, Amhara, Sidama and Tigray regions. Figure 4 presents a summary of loans received by the SMEs. A total of 197 SMEs has received loans from with an amount of 3.16 billion ETB, which reached 56% of the target of the project.

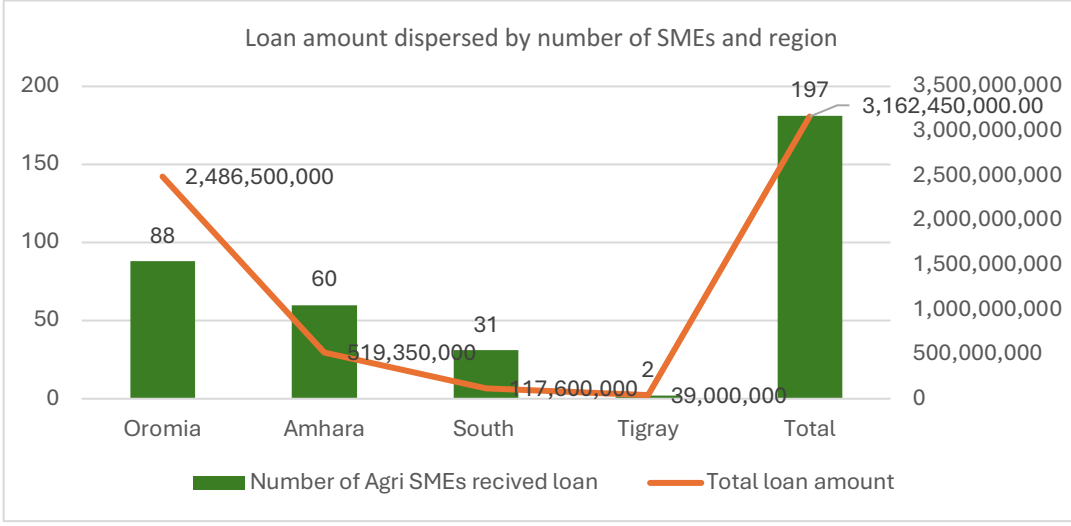

Figure 3. Number of SMEs and loan amount (ETB) provided across target regions

3.3. Development of sustainable Agri Hub business model

3.3.1. Assessment of methodologies and tools

Agri-hub has assessed the methodologies and tools developed by the project for BDS support by an external consultant with the objective of assessing the quality and efficiency of the services provided, modalities of access to the services by the SMEs, modalities of collaboration with partners and service providers, and internal organization of ATI for the delivery of the services to the SMEs. Hence, the existing Agri-Hub BDS tools were assessed and mapped for potential improvements. For instance, the project has finalized a play book to be used as a learning document for AOSS business. Twelve methodologies and tools were assessed and documented.

3.3.2. Creating partnership with stakeholders for standardization of BDS tools

Efforts have been undergone by Agri-Hub project to increase number of services providers under with the overall rationale to strengthen the BDS ecosystem. Thus, so far, the project has collaborated with EDC, Devoted Consulting PLC, Target Consulting PLC and Fortune consulting PLC to develop business modules and provide business skill development training, Advisory service and mentorship service. Furthermore, the project has secured international training tools from AMEA (Agribusiness Market Ecosystem Alliance) and BIC Ethiopia to standardize the Agri SMEs business skill training preparation and delivery.

In addition, the project has also worked with Canadian Executive Service Organization (CESO) and obtained their support of team building programs for Agri-Hub project team that help project team to enhance project performance. Moreover, 3 BDS service providers were identified and capacitated in Oromia, Amhara and SBB regions for BDS services at regional levels. In total, the project has partnered with 5 BDS providers.

3.3.3. Capacity building of BDS service providers

Agri-Hub also conducted networking and consultation workshops for BDS service providers. The project has organized this workshop through engaging 29 BDS providers operating and supporting Agri-SMEs in target regions. The session mainly focused on identifying and networking with BDS providers, creating linkage with Agri-SMEs and relevant business partners, getting experience and updates from Ethiopian Business Service Providers Association (EBSPA), and developing joint solutions to common challenges.

4. Conclusion and Recommendations

The project provided business skill development support for 12 categories/types of 1,216 SMEs through a 4-tiered BDS model with various activities that include business diagnosis and training need assessments, business skill training delivery, provision of business advisory service, accounting mentorship, group networking and experience sharing, and provision of tools & software to help them grow and scale up their business. Practical and customized capacity building in business found a key success factor for improved performance of SMEs. The continuous coaching and advisory

services have initiated SMEs to diversify their products and organizing networking, which creates the way for better B2B linkages with other similar businesses.
The project demonstrated that tailored training significantly enhances the performance of Agri-SMEs, while networking and experience-sharing workshops strengthen business-to-business linkages and improve access to market information. National access to finance workshops and regional finance fairs were instrumental in engaging financial institutions and promoting sustainable financing opportunities for SMEs. Strong collaboration with project partners and business development service providers further improved implementation outcomes. Ongoing coaching and advisory support encouraged SMEs to diversify their products, and region-specific workshops contributed to better governance, regulatory frameworks, and coordination among stakeholders and Agri-SMEs.
The project also identified major challenges that hinder the business expansion of the SMEs. Some of the challenges are internal for which the SMEs can manage them. Some other challenges, however, are external for which the SMEs have little or no control at all. Initially, there was confusion around BDS tier distinctions, selection criteria, and enrollment procedures, which was addressed by consolidating one BDS tier and updating definitions, criteria, and recruitment processes to include SMEs beyond ATI projects. Security concerns that restricted staff movement for advisory and project activities were mitigated by engaging local experts and using virtual communication with SMEs. To respond to the growing demand for business advisory and mentorship services, the project hired additional staff and expanded the role of BDS providers to include advisory services alongside training. Delays caused by lengthy donor review and endorsement processes were managed through close follow-up, frequent communication, timely escalation of delays, and the consideration of framework agreements for major procurements. Finally, high SME staff turnover was addressed through continuous follow-up support and training for SME owners and managers on staff retention strategies.

Based on the practical experience of the project, the following, among others, are recommended.

- Additional and continued business skill development support should be provided for the targeted SMEs as all targeted SMEs are not provided with most types of business skill development support, which is required for SMEs to be successful.
- More efforts are required to address the current untouched financial demand of SMEs through additional capacity development of Agri-SMEs, as well as closely working and capacitating financial institutions in development of financial services adapted to Agri-SMEs, creating incentive mechanisms for financial institutions including credit guarantees, and linking SMEs and financial institutions.
- Further support should be also rendered through the project on the application of accounting software.

- Finally, additional activities that enhance project sustainability, like strengthening SMEs' associations, and private BDS providers and their associations, are required. Moreover, best practices of some SMEs should be properly documented and shared in continuous way.

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Enhancing Financial Inclusion for Smallholder Farmers through Rural Savings and Credit Cooperatives Capacity Building

***Dagnachew Seyoum, Awet Tekie, Solomon Legese, Berhane Kidanu, Yibekal Dinku, Bikila Lamesa, Tekaligne Petros, Fisseha Tilahun and Beshana Taso**

Ethiopian Agricultural Transformation Institute (ATI), Digital Agriculture and Finance program, P. O. Box: 708, Addis Ababa, Ethiopia
*Corresponding Author E-mail: Dagnachew.Seyoum@ati.gov.et

Abstract

Rural Savings and Credit Cooperatives are locally driven financial institutions that operate in rural areas, promoting economic growth by mobilizing savings and offering loans to individual farmers, families, and small businesses within the community. They are recognized for their potential in providing short-term financing for agricultural production and supporting off-farm income-generating activities, particularly in regions where both the government and private sector have been unable to meet financial needs. However, Rural Savings and Credit Cooperatives has been facing challenges such as poor governance, lack of strategic business plans, inadequate infrastructure, and poor skills of the personnel. To address these limitations, the "Rural Savings and Credit Cooperatives Capacity Building (RuSACCO) project was designed in 2019. The project among others aims to develop strategic business plans, enhance infrastructure development and capacity building of the target groups with ultimate purpose to enhancing financial Inclusion for smallholder farmers. Findings show that the RuSACCO project has significantly improved the performance and efficiency of cooperatives by addressing capacity gaps and providing extensive training to union managers and experts. Also, the initiative has enhanced governance, internal operations, and financial management, thereby increasing access to finance for smallholder farmers. Similarly, the project helped in improving infrastructure and capacity of the union leaders on important finance management skills. These efforts have fortified RuSACCOs' ability to provide demand-driven financial services, ensuring stability and growth in the agricultural sector. The paper also highlights challenges, such as poor business management skills of the RuSACCOs employees and lack of standardized operational policy and regulatory framework for RuSACCOs to perform their duties as desired.

Keywords: Access to finance, farmers cooperative's, loans, union

1. Introduction

Access to financial services is critical to develop the rural development and commercialize Ethiopia's agricultural sector. However, a smallholder farmer's/pastoralist's access to finance and credit system is a major determinant for the adoption and sustained use of agricultural inputs, such as fertilizer, improved seeds, forage, animal drugs and agro chemicals. Access to finance allows a farmer/pastoralist to produce surpluses products for the market and raw materials for agri-business

industry development. Access to finance by rural financial institutions and private sectors also facilitates aggregations as well as value-addition processing and strengthen linkages to markets for smallholder farmers and pastoralists.

As Rural Saving and Credit Cooperatives (RuSACCOs) are close to farmer/pastoralist, strengthening these institutions will develop confidence and enhance the use of financial services by smallholder farmers. Creating strong and self-sustaining rural financial institutions capable of delivering rural sector-adapted financial services to smallholder farmers/pastoralists, cooperatives, and Micro Small and Medium Enterprises /MSMEs/ is essential. To address these challenges, the National Financial Inclusion Strategy (NFIS) was launched in September 2017. The strategy stipulates that the former Agricultural Transformation Agency /ATA/, the former Federal Cooperative Agency /FCA/, and Ministry of Agriculture /MoA/ are responsible for strengthening the RuSACCOs based on the best international practices.

Accordingly, in 2017, the former ATA, and the current ATI in collaboration with Federal Cooperatives Agency and Rabo Bank have conducted a study to transform Ethiopian SACCOs by initiating a project called ''Rural Savings and Credit Cooperatives Capacity Building'' (ATA,2017). The findings of this study revealed the need to establish an apex body (Rural Cooperative Bank) to transform the fragmented and tiny Rural Savings and Credit Cooperatives /RuSACCOs/ into viable and competent financial institutions. The establishment of cooperative bank was included in the amended proclamation for the establishment of Cooperatives and presented to the cabinet for endorsement. Unfortunately, the cabinet instructed ATI to work on building the capacity of the institution before embarking on the establishment of a Cooperative Bank.

Strengthening RUSACCOs have enhanced internal integration by creating linkage and coordination with other financial institutions, mainly MFIs for ensuring the sustainability of Input Voucher Sales System (IVS) as well as by introducing weather index insurance (WII) in a cost effective and efficient manner. This has created better financial access for smallholder farmers/pastoralists through improving service delivery for procurement and distribution of agricultural inputs and adoption agricultural technologies. This has greatly contributed to boosting production and productivity of farmers/ pastoralist and ultimately contributed to the broader goal of improving rural livelihoods.

The objective of this paper is to assess the critical roles that RuSACCOs play in improving financial access for smallholder farmers/pastoralist in Ethiopia. It also highlights the significant barriers faced by marginalized groups, such as the poor, youth, rural communities, and women, in accessing financial services. The findings will also provide suggestions to better strengthen the platform and support the Ethiopia's smallholder farmers /pastoralist located in marginal areas.

2. Material and Methods

2.1. Description of implementation sites

The Project is implemented across various regions in Ethiopia, with a focus on ACC implementation districts and clusters, as well as areas with significant agricultural activities. Key implementation sites include Oromia, Amhara, Tigray, Sidama, south Ethiopia, Southwest Ethiopia, and Central Ethiopia. These regions were chosen due to their high concentration of smallholder farmers and the presence of numerous RuSACCOs in need of capacity enhancement.

2.2. Operational Design and implementation model

The operational design of the Project is centred around a comprehensive and systematic approach to enhancing the capabilities of the institution. This involves identifying gaps using project-developed diagnostic tools and providing targeted interventions to address these gaps. Training programs are conducted for saving and Credit Cooperatives union managers to ensure that they can effectively implement these diagnostic tools and interventions. The project also emphasizes the importance of a supportive policy and regulatory environment, advocating for changes that facilitate the growth and sustainability of the institutions. By systematically tracking performance improvements and interventions over time, the project aims to build resilient and self-sufficient RuSACCOs that can provide diversified financial services to smallholder farmers.

The project focuses on enhancing the performance and efficiency of RuSACCOs by clearly defining roles between primary and secondary societies, improving governance, and developing strategic business plans. It includes investing in infrastructure, such as establishing a central shared services and digitalizing core banking systems and providing extensive training to union managers and experts. The project also emphasizes implementing standardized processes, offering tailored financial products to meet the needs of smallholder farmers/pastoralist, and conducting regular monitoring and evaluation to track progress and address emerging challenges.

Additionally, the project emphasized the importance of creating a supportive policy and regulatory framework to facilitate the growth and sustainability of financial institution. Strategic interventions were prioritized to address gaps in liquidity, product offerings, and operational capabilities, ensuring that the institution could effectively mobilize savings and provide diversified financial services. This comprehensive approach aimed to build the resilience and self-sufficiency of RuSACCOs, ultimately contributing to the broader goal of improving rural financial services and supporting agricultural development.

2.3. Data collection and analysis

2.3.1. Data collection

The data collection and assessment rely entirely on secondary data collected through a comprehensive desk review of various project documents. These include Capacity Building Roadmap of the project, Rural Financial Services (RFS) Strategy, annual progress reports and quarterly regional reports, diagnostic tool assessment reports, and the analysis report of joint monitoring visits. The desk review proved effective in extracting essential information from various formats, making it accessible to a broader audience, including other projects within ATI and its partners. Additionally, documents such as capacity building project management plan, sector capacity building roadmap, project design documents, and other relevant technical materials were reviewed.

2.3.2. Data analysis

The collected data were analysed using content analysis, systematically organizing the findings into themes and sub-themes, including project targets, interventions, specific supports provided, outcomes, partnerships, women's leadership roles, women's empowerment, and challenges faced by them and the project itself. Additionally, the information gathered through the desk review were analysed using subject analysis, categorizing the findings into similar themes and sub-themes such as project targets, interventions, specific supports, outcomes, partnerships, women's leadership roles, women's empowerment, and challenges faced by the RuSACCOs and the projects.

3. Results and Discussion

3.1. Improving efficiency of rural saving and credit cooperatives

Capacity assessment and gap identification using a diagnostic tool was carried out on 3980 RuSACCOs. These efforts were complemented by regional workshops aimed at capacity building of the personnel to effectively utilize the diagnostic tool developed for performance assessment.

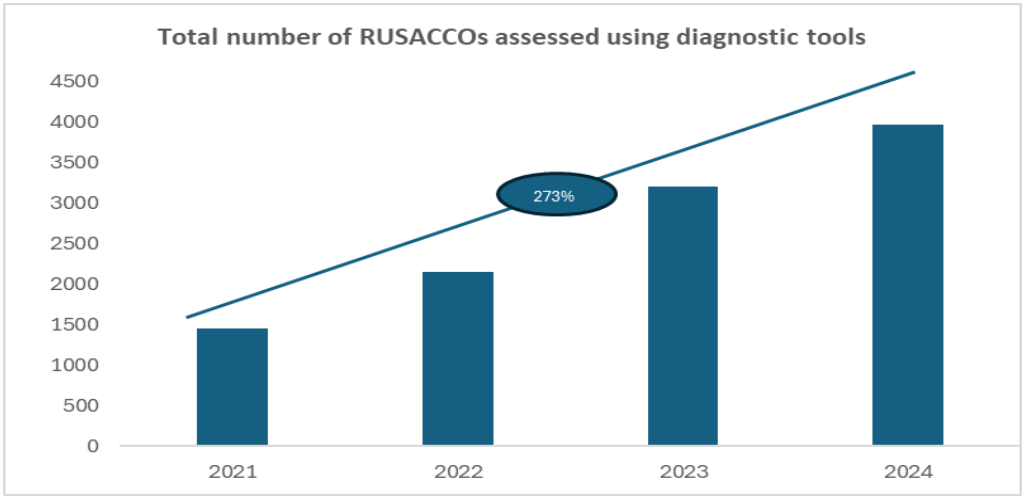


Figure 1. Number of RuSACCOs assessed using diagnostic tool (2021-2024)
Source: RuSACCO capacity building project terminal report (2024)

As shown above under Fig.1, in 2021, 1,447 RuSACCOs were assessed for their capacity and challenges they were encountered to perform. This number rose significantly to 2,139 in 2022. The upward trend continued in 2023 with 3,193 assessed, and by 2024, the number reached 3,980 showing 273% growth compared with initial assessment in 2021. These figures demonstrate a consistent and substantial increase in the number of RuSACCOs being assessed each year. The year-on-year growth suggests that the diagnostic tool is being increasingly adopted and utilized, reflecting a growing focus on evaluating and improving the performance and management of these organizations over time.

The use of diagnostic tools has revealed several key findings. For instance, the tools have identified significant challenges, including low member participation, inadequate professional skills, limited loan availability, and weak management practices. Additionally, the assessments highlighted the need for more training opportunities and better awareness creations on income-generating activities among members. Despite these challenges, the diagnostic tools also uncovered opportunities, such as supportive government policies, infrastructure development, and capacity-building efforts. Addressing these issues can help transform RuSACCOs into more viable and competitive financial institutions.

To effectively implement the diagnostic tool assessment, technical and practical trainings were provided to 1,157 union managers of whom 346 are women farmers, credit, and accounting experts, as well as regional and zonal subject matter specialist. The technical and practical trainings were supported by 120 laptop computers provided to the unions as part of the project grant.

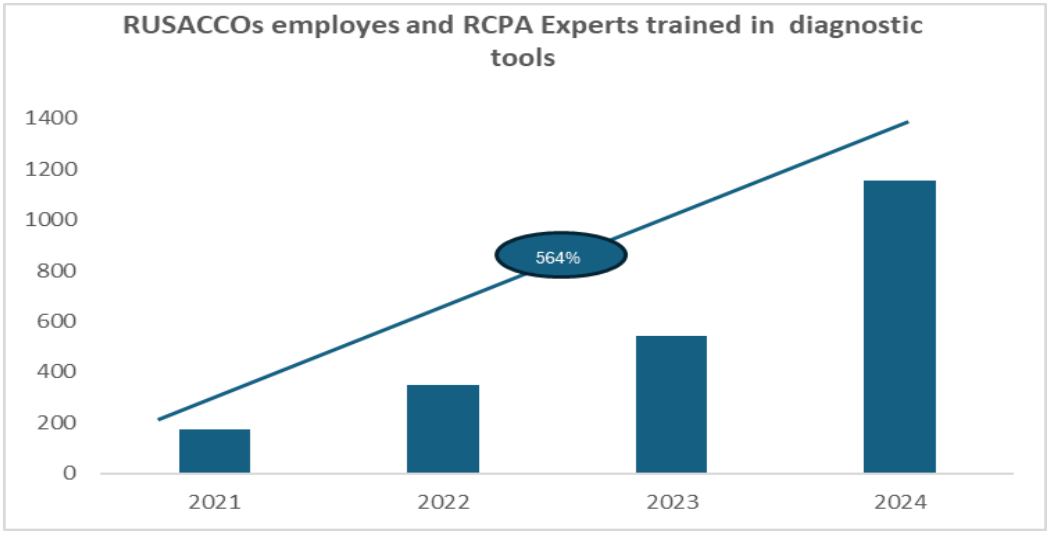


Figure 2. Number of RuSACCO employe & RCPAs experts trained in diagnostic tool (2021-2024)
Source: RUSACCOs capacity building project terminal report (2024)

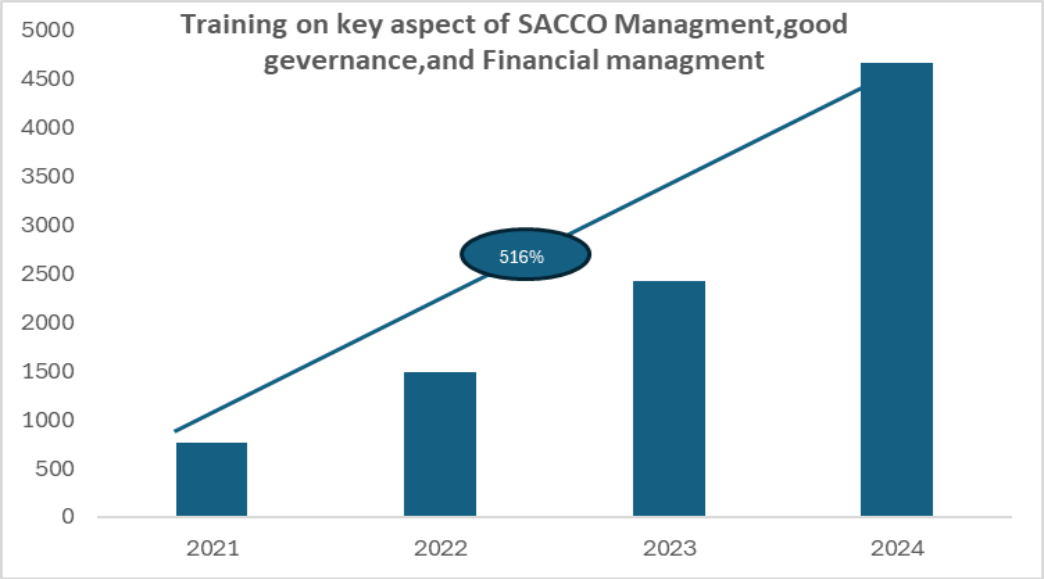
Figure 2 above shows, the number of RuSACCOs employees and regional cooperative promotion agency (RCPA) experts trained in the diagnostic tool from 2021 to 2024. In 2021, only 174 employees both from RuSACCOs and RCPA experts were trained. This number rose significantly to 347 in 2022. The upward trend continued in 2023 with 544 individuals trained, and by 2024, the number reached 1,157, showing 564% growth compared with an initial 174 employees trained in 2021. This demonstrates a consistent and substantial increase in the number of individuals being trained each year. The year-on-year growth suggests a growing focus on equipping employees of RuSACCOs and RCPA experts with the required skills and knowledge to effectively run their business. This trend reflects a commitment to improving the performance and management of RuSACCOs and RCPA through enhanced training and capacity building.

Following gap identification and feedback from the assessment, RuSACCOs have actively worked to address gaps in areas such as governance, internal operations, cooperative functions, improve member participation, finance, resource management, and institutional coordination and infrastructure developments. Their efforts aim to efficiently provide financial services and products to smallholder farmers/pastoralist, ultimately enhancing access to finance for them and enabled them for efficient and effective service delivery system using the diagnostic tools as a guideline.

This assessment revealed that capacity building conducted for 2222 RuSACCOs employees and RCPA experts which have improved and strengthened their governance and management, increased membership, managed farmers' financial resources to create access to finance for smallholder farmers/pastoralist and enhanced their institutional infrastructure and facilities.

3.2. Enhancement of rural saving and credit cooperatives service delivery

A total of 4,674 leaders, including 639 women trained on essential business management skills. This includes training on finance management skills, credit management, asset management, and debt risk management. Additionally, 2,390 top level leaders, (506 women) both from the union and primary cooperatives were received especial training on topics such as good governance, financial management and improved service delivery strategies and operational standards.



Source: RuSACCOs capacity building project terminal report (2024)
Figure 3. Training on key aspects of management, good governance, and financial management (2021-2024)

As we have seen above in Figure 3., the number of RuSACCO employees trained in key aspects of SACCO management (good governance, and financial management) has increased significantly from 2021 to 2024. For example, in 2021, 758 employees were received training. This number rose to 1,489 in 2022, continued to grow to 2,431 in 2023, and reached 4,674 by 2024. This pretty demonstrates a consistent increase in trained personnel each year for RuSACCOs employees. This year-on-year growth highlights a growing focus on equipping RuSACCOs with essential skills and knowledge, reflecting a strong commitment to improving their performance and management through enhanced training and capacity building.

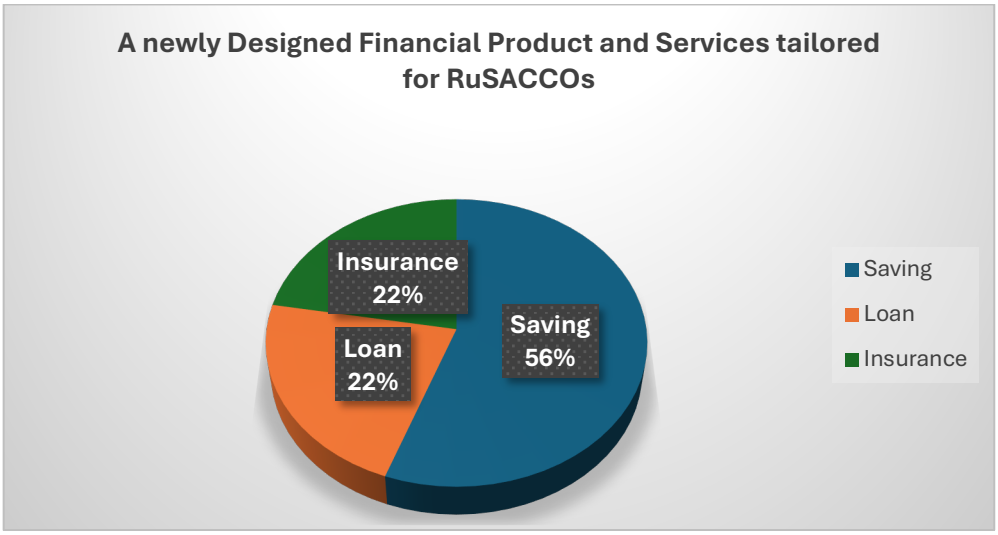
The assessment from the study indicated that the training offered for RuSACCOs and RCPA has greatly helped in updating the existing and new internal procedures, policy, manuals, and regulations, and these ultimately equip the trainees with important knowledge and skills to effectively run their respective business. It also enhanced their internal governance and financial performance and enabled them to provide demand-driven services for smallholder farmers. On top of this, the training empowered the leaders with appropriate knowledge and skills to improve their performance through creating robust financial institutions that offer tailored financial products to smallholder farmers and facilitate easy access to finance.

According to the project terminal report (2024), by the end of the project, nearly 1 million SHFs were reached through credit and saving products provided by the RuSACCOs. The training that was offered to selected leader of farmers on financial literacy has improved

the financial literacy and management skills of smallholder farmers. In addition to capacity building for farmers, training modules and risk management strategies, including asset liability management, have been developed and reviewed by the Ethiopian Cooperatives Commission's Financial Cooperatives. These important documents have been validated and approved by the Ethiopian Cooperative Commission (ECC). Also, these materials, along with policies on asset liability and risk management for Ethiopian savings and credit cooperatives, have been translated into three local languages: Amharic, Afan Oromo, and Tigrigna, for use as training materials.

3.3. Enhancement of financial products and services

According to the final assessment of the project terminal report (2024) 95% of the work aimed at delivering a range of financial products and services tailored to the financial requirements of RuSACCO has been completed. This product development has been contributed in developing ten financial products and services that meet the specific needs and interest of the institution and SHF receptively. These offerings are primarily designed to address the credit needs, insurance services and promote saving of smallholder farmers with overall purpose to improving farmers access to financial resources (Fig.4)



Source: RuSACCO capacity building project terminal report (2024)
Figure 4. Financial products or services developed for SACCOs/RuSACCOs

The pie chart displays the distribution of financial services and products developed, revealing that 56% are saving products, 22% are loan products, and 22% are insurance products. This visual representation effectively highlights the proportion of each type of product developed. The products are focused on savings, credit, and insurance, which are highly preferred by SHFs.

These financial products are highly preferred by smallholder farmers because they address their unique challenges and help them manage their finances more effectively, ensuring stability and growth in their agricultural activities. Following the collaboration with the Ethiopian Cooperative Commission (ECC) and the consultant, the financial products and services have been developed and are now prepared for pilot implementation.

4. Conclusion and Recommendations

The project has markedly enhanced the performance and efficiency of RuSACCOs by identifying capacity gaps and delivering extensive capacity building to union managers, experts and SHF. This initiative has also improved governance, internal operations, and financial management of RuSACCOs thereby increasing financial access for smallholder farmers. Additionally, the project upgraded the infrastructure and facilities for RuSACCOs to function properly and efficiently. This has helped reaching of nearly, 1 million smallholder farmers through developing tailored financial products and services, promoting savings, enhancing credit and insurance services.

The RuSACCO Capacity Building Project faced several challenges among which budget constraints is the major one. This limitation hindered onetime completion of tasks, including those assigned to regional project teams. Law enforcement activities in the Amhara region further disrupted planned works. Additionally, the crisis in the Tigray region led to the theft of essential infrastructure, such as laptops and computers, complicating project implementation. To address these challenges, the team engaged in discussions to make informed decisions on effectively utilizing the remaining budget. Plans are in place to resume work in the Amhara region once conditions improve and to support unions by purchasing necessary equipment like computers, laptops, and printers, which is expected to decisively resolve the issues.

During project implementation, several important lessons emerged: clearly defining roles between primary and secondary societies (Unions) is essential to prevent duplication of efforts; strong governance and strategic business planning are critical for building RuSACCO capacity and long-term success; and investment in infrastructure, including a central shared services centre (SCS) and digitalized core banking systems, is vital. The use of diagnostic tools enabled identification of key constraints and delivery of targeted interventions, significantly strengthening RuSACCOs' ability to provide financial services to smallholder farmers. Additionally, capacity building for RuSACCO and RCPA staff improved operational efficiency, while standardized processes and sound financial management practices supported sustainability. Continuous monitoring and evaluation also proved crucial for tracking progress and responding effectively to emerging challenges.

To build on the project's successful outcomes, it is recommended that future implementation and scale-up focus on several interrelated actions. First, capacity building programs for RuSACCO leaders, staff, and smallholder farmers should be

continued and expanded, with a strong emphasis on advanced financial management, governance, and digital literacy in order to further improve operational efficiency and sustainability. At the same time, sustained investment in both physical and digital infrastructure is essential, including upgrading existing facilities, implementing robust IT systems, and establishing a centralized client database to streamline operations and enhance service delivery. In addition, the development of a broader range of financial products tailored to the specific needs of smallholder farmers should be prioritized; therefore, collaboration with key stakeholders to provide microloans, insurance products, and savings schemes is necessary to address the unique challenges of rural communities. Moreover, embracing digital solutions such as digitalizing financial transactions, expanding mobile banking platforms, and introducing a shared services centre will improve efficiency and extend outreach. Finally, identifying and replicating successful models and best practices from the project to other regions, while simultaneously promoting financial literacy and business skills among smallholder farmers and rural communities, will empower them to make informed financial decisions and maximize the benefits of available financial services.

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Review of Selected Post-Harvest Technologies Developed for Root Crops in Ethiopia

Amanuel Erchafo Ertebo

Ethiopian Institute of Agricultural Research, Melkassa Agricultural Research Center, Department of Agricultural Engineering Research Process, P.O. Box 436, Adama, Ethiopia.
Corresponding author: amanbaaman40@gmail.com

Abstract

This review was conducted to understands the status of postharvest technologies developed for root crops. It was meant to be used to generate secondary information for making minor improvements, conducting participatory evaluation, scaling up and distribution of selected technologies. The assessment was carried out on the selected postharvest technologies developed for root crops in Ethiopia. The review was conducted on available models of decorticators, pulverizers, fermenters, washers, polishers, boilers, peelers, graders, and diggers. Based on the available literature the postharvest technologies development related to root crops are not still significant when compared to grain crops. The study indicated that the involvement of the private sector in the development of postharvest technologies for root crops was low, but the government institutions had made good progress. For example, technology development for enset processing has showed good progress. Further research and development are needed to improve root-crop processing technologies and make them more accessible to farmers. Based on the findings of this study, it is suggested that researchers, institutions, and all stakeholders should explore innovative technologies and dissemination approaches to address the problem in the root crop processing area.

Keywords*:* Biolers, decorticating and grating machines, polisher, postharvest loss

1. Introduction

Agriculture is a key component of Ethiopia's Growth and Transformation Plan, which aims to improve the quality of life for its citizens, enhance food self-sufficiency, and increase income generation. Agricultural production is not only fundamental to improving nutrition, but it is also the main source of income for many people. Crop production is vital for food security, economic stability, and the provision of raw materials for various industries (Garcia-Diez *et al*., 2021). Cereals are the leading group of crops produced worldwide, with 3.1 billion tones produced in 2022**,** followed by sugar crops at 2.2 billion tones, vegetables at 1.2 billion tones, oil crops at 1.1 billion tones, fruit at 0.9 billion tones and roots and tubers at 0.9 billion tones (Brief, 2022).

Root crops have edible underground plant parts, including true roots like taproots and tuberous roots and structures that are not technically roots like bulbs, corms, rhizomes, and stem tubers cultivated for their food value and are a vital part of food

security, especially in developing countries. Root and tuber crops are a vital food source in Ethiopia, grown in various agro-ecologies and production systems. The major root and tuber crops include cassava, yam, potato, sweet potato, enset, taro, beets, carrots and turnips. Based on the demand for their processed products, root crops such as enset, cassava, potato, turmeric, and carrot were used in this investigation.

Enset is one of the most extensively utilized foods in southern Ethiopia. It is frequently offered to Ethiopians as their primary source of food security because of its importance and versatility. In the southern region of Ethiopia, it offers a sustainable food supply to roughly twenty-four million people (Olango *et al*., 2014). Processing and preparation take a long time, and this work is carried out by women. The conventional processing methods are complex, laborious, and unhygienic, causing great stress for working women and resulting in a significant loss.

Cassava is the other root crop which is popular as a food in Africa. Because of its adaptability, it is considered as the foundation of food security (Immanuel *et al*., 2024). It is an important staple food in Ethiopia as well, especially in the south, southwest, eastern, and northwest regions of the country. The most widely used processing method for processing of cassava tuber is the manual method, which is performed as this method, however, makes the process tedious, labor-intensive, time-consuming, and less effective. The resulting processed product is, low in quality and reduced quantity.

Potatoes are starchy underground tubers that are a staple food in many parts of the world. Potatoes are the world's most important tuber, contributing to the energy and nutritional needs of over a billion people (Milkias & Keba, 2021). Ethiopia has a significant potential for potato production, with suitable agro-ecological conditions. Ethiopia's average potato productivity is around 13.27 tones per hectare, which is lower than the global average of 21.77 tons per hectare (Milkias & Keba, 2021).

Turmeric is one of the most significant spice crops, supporting many people in their lives. As a key component of the regional sauce '*Alicha Wot'*, Ethiopian homemakers consider turmeric to be one of the most flavorful spices. The absence of post-harvest technologies for turmeric in the regions where it is grown is an urgent issue for turmeric growers.

Carrot is one of the most popular root vegetables and one of the most widely consumed agricultural products by billions of people worldwide (Barzee *et al*., 2019). It is one of the top ten vegetable crops in the entire world in terms of economic significance. Technology-induced automation has significantly reduced the amount of time and effort that humans must spend.

Problems associated with root crops are that they are the most perishable crops, which can deteriorate within two or three days after harvesting, leading to significant post-

harvest losses if not handled, processed and stored properly. The primary purposes of processing root crop is to enhance the quality and quantity of the product, ensure uniform drying, minimize drying time, and lessen spoilage, damage, and other losses that may occur during the post-harvest period, which can be considerable, particularly for perishable crops. Hence, the objective of this paper was to review the status of selected postharvest technologies developed for root crops to facilitate future interventions that will make the technology available.

2. Materials and Methods

An assessment on the status of selected post-harvest technologies for root crops was conducted on decorticators, pulverizers, fermenters, washers, polishers, boilers, peelers, graders, and diggers. The review for root crops focused on processing technologies for enset, potato, turmeric, cassava, and carrot. The status of these selected post-harvest technologies was reviewed in terms of key performance parameters. These key performance indicators include capacity, efficiency and percentage of loss. Based on their impact on root crop processing, technologies such as the decorticators, pulverisers, fermenters, washers, polishers, boilers, peelers, graders, and diggers were selected for review. The method employed during the review involved assessing the performance of the technologies under the main performance indicators. The methodology used in this study for reviewing the status of technologies was a secondary data collection approach, encompassing a review of journal and conference articles by previous authors, internet sources, newspapers, and magazines. Additionally, previously conducted yet unpublished research by the Melkassa Agricultural Research Centre and other institutions was included in the review. Thus, this research highlights the need for interventions to ensure the status and performance of the selected technologies.

3. Results and Discussion

3.1. Enset processing technologies

Enset processing technologies include traditional methods like using a watani or flat wooden board for decorticating, a javga or wooden tool for pulverizing, and a "sibisa," longitudinally split bamboo, for scraping. Improved technologies include enset scrapers, squeezer machines, and fermenting machines.

3.1.1. Traditional Enset processing tools

The conventional enset processing tools include Watani, Javga, Sibisa, and Fermentation pits or boxes. Watani is a flat, locally prepared wooden board used to decorticate (remove the outer layers) the enset pseudostem. Javga is a wooden tool with two ends: one serrated for pulverizing the corm and macerating bolla gamma.

3.1.2. Mechanical Enset processing technologies

The mechanical enset processing technologies include a decorticator, grater, scraper, and squeezers. Enset scrapers are used to separate the leaf sheath from the fiber, whereas decorticating machines are used to separate the fibre from the stem.

Engine-driven enset decorticator : A study on this decorticator was conducted to address the issues related to enset processing (Woldeyesus *et al*., 2025). The result for this machine reported that the maximum decorticating capacity of 97.88 kg h^{-1} was obtained at a drum speed of 850 rpm under 1 mm concave clearance and the feeding rate of 0.077 kg s^{-1}. The highest decorticating efficiency of the machine was 98.98% at a drum speed of 850 rpm, with a concave clearance of 1 mm and a feed rate of 0.077 kg $s^{-1.}$ while the lowest loss of 1.03% was recorded at drum speed 850 rpm, concave clearance 1 mm and feed rate 0.077 kg s^{-1}. The highest fuel consumption of 15.91 mL kg^{-1} was observed at drum speed 950 rpm, feeding 0.077 kg s^{-1} and concave clearance 1 mm as reported. The material selected for fabricating this decorticator was free from corrosion. However, as a limitation, the throughput capacity of the machine was low when compared with the output range of machines, as well as other developed technologies, so it needs further improvement on the main components to increase its output. Besides, the engine setting needs minor improvement. The enset producers are encouraged to use this machine for enset decortication after optimisation.

Improved warqe decorticating machine: This machine had functional parts, including a drum beater, breastplate, reduction gears, collecting box, chain and sprocket, feeding table, pulleys, transmission belts, rollers, engine seat, and bearings (Workesa *et al*., 2021). The maximum decorticating capacity of 255.38 kg h^{-1} was obtained at a drum speed of 850 rpm, concave clearance of 1 mm, and a feeding rate of 0.074 kg s^{-1}. The maximum decorticating efficiency of 98.97% and minimum pulp loss of 1.03% were achieved at a drum beater speed of 850 rpm and a concave clearance of 1mm. From the review, the performance status of this improved decorticator indicates that it still requires a detailed redesign for optimal processing output during use.

Improved kocho, bulla, and fibre production machine: The main components of the modified enset sheave decorticator were a 3 hp Gasoline engine as a source of power, a decorticating drum with blades, an inclined plate, a clearance adjuster, a kocho collector bucket, and a pair of rollers (Dalelo & Alandu, 2022). The report indicated that the average decorticating capacity of the machine was 57.63 kg h^{-1}. The machine decorticating efficiency was 89.5% with an average fibre cleaning efficiency of 77.64% as well as with 10.16 % broken fibre and 1.92% un-decorticated kocho. The overall status for this improved machine indicated that this machine is not efficient for processing enset. Therefore, it must be improved for end-user use; otherwise, it is better to use other, more effective machines that have good performance results.

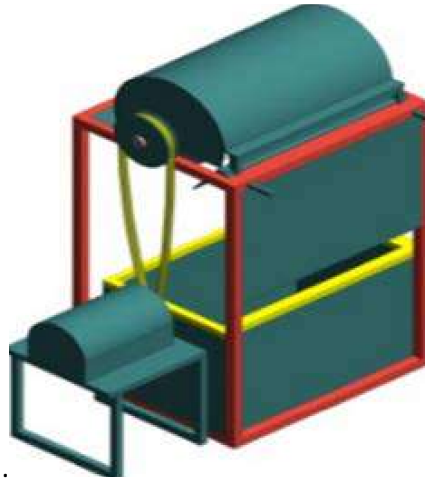

Figure 1**.** Enset processing machine

Manual enset decorticator: This manual enset decorticator was improved by the Melkasa Agricultural Research Center. The center has tried to improve the clamping mechanism of the decorticator. This improved decorticator, as reported by the center, decorticate one enset plant with in 3.36 h, with a decorticating efficiency of 91.00%. From the reviewer point of view, its status indicates that it is not significantly different from the conventional method, so it is preferable to use a mechanical decorticator.

3.1.3. Grating machines

Engine-driven corm grating machine: This machine consists of three main units: the hopper, the grating drum, and the delivery chute (Kibi, 2018). Based on the results reported by the author, the mean grating capacity of 1048.3 kg h^{-1} was recorded for the grater. The optimum capacity of 1277 kg h^{-1} was observed when the drum was operated at a speed of 2200 rpm using Sharte variety; whereas the minimum capacity of 604.0 Kg h^{-1} was observed when the drum speed was 2000 rpm using Baladati variety. From the test report, this machine can be used by farmers for all varieties of enset corm. Based on the review, this machine requires participant evaluation and demonstration to enhance awareness for end users and to address the problem of grating enset corm using conventional methods. Furthermore, it would be beneficial to multiply and distribute it to end users.

Figure 2. Corm grating machine

Enset corm pulverizer: This pulveriser is mainly composed of a pulverizing unit, feeding table and transmission unit. This corm pulverizer recorded a capacity of 320-360 kg h^{-1}, which is more than 150 times compared to the traditional practice as reported by Kebede *et al*. (2018). Its status indicated that the machine is not recommended for pulverizing corm because there is a problem with the feeding mechanism, which causes staking. Currently, it is presented in the Melkassa Agricultural Research center without any function. So, the pulverizer is not satisfactory and does not need to be scaled out to the end users for processing corn, which is not efficient compared to the conventional method.

Corm pulverizing machine : This enset corm pulverizing machine (Figure 3) is developed by Ertebo & Girma (2024). It is composed of a hopper, housing, drum, chute, frame, and power transmission unit. The performance result, as reported by authors showed that under operating speed of 1800 rpm and a feeding rate of 10 kg min^{-1}, a maximum pulverizing capacity of 721.4 kg h^{-1} was found. Likewise, at a speed of 1600 rpm and a feeding rate of 15 kg min^{-1}, the minimum pulverizing capacity of 611.6 kg h^{-1} was found. The highest pulverizing efficiency of 97% was found at an operational speed of 1800 rpm and a feeding rate of 15 kg min^{-1}, whereas the minimum pulverizing efficiency of 93.5% was found at an operating speed of 1600 rpm and a feeding rate of 10 kg min^{-1}. The percentage of loss for this machine ranged from 3.5% to 6.5%. The performance status for this motorized machine indicated that a minor improvement was needed for the optimization of its output for processing enset by end users before using it.

Figure 3. Corm pulverizing machine

3.1.4. Integrated machines

Integrated enset processing machine: This integrated machine was developed by Adugna *et al*. (2025). It is powered by a single-phase electric motor, enabling an integration of four unit operations: decortication, corm grating, pulverization, and bulla extraction. The status for this machine indicated that this designed integrated enset processing machine may be utilized by farmers for processing enset because it was well designed, but it is only at the design stage and has not been fabricated and evaluated.

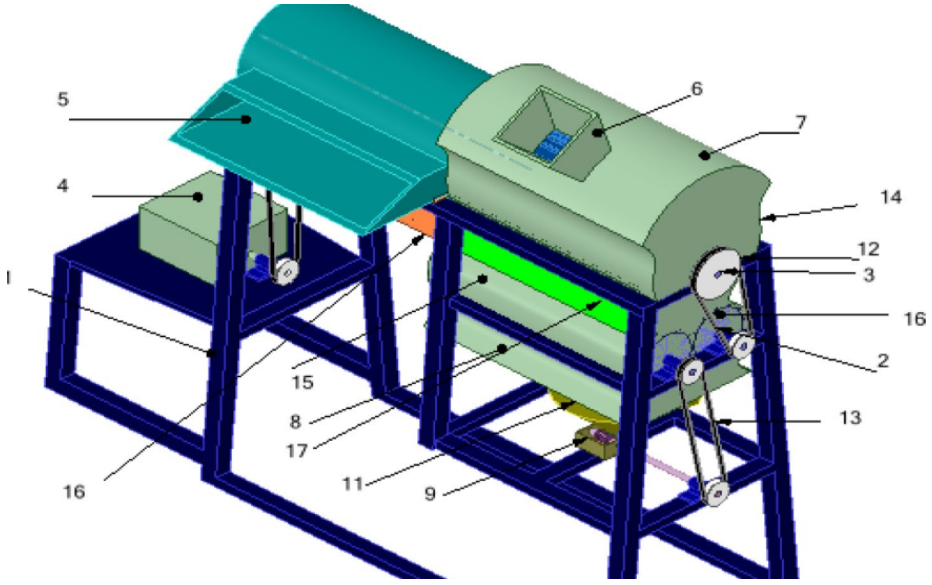

Figure 4. Integrated enset processing machine

Corm grater and leaf sheath decorticator: The corm grater and leaf sheath decorticator machine was developed by Kibi & Tefera (2024). Based on the results obtained, the grand mean grating capacity of 1658 kg h^{-1} for corm and decorticating capacity, decorticating efficiency of 497 kg h^{-1} and 90.3% for leaf sheath was recorded for the prototype at 1 mm concave clearance during processing. From a review of its status, this machine was easy to transport from place to place and was simple for use by farmers. It was suggested to conduct an improvement on the hopper and feeding unit and participant evaluation of the machine for further use by farmers. This integrated version is a modified one from the previous grating machine, but no more different at the first one.

Figure 5. Corm grater and leaf sheath decorticator

3.1.5. Fermenter box

This fermenter consist of a frame made from angle iron used for supporting and carrying the whole body of the fermenter box (Gizachew, 2019). As it is reported, the fermenter has three compartments and can ferment up to 300 kg at once, and its volume is 0.441m^3. From the point of view of the reviewer, this fermenter is not used for large-scale fermentation of processed enset, and its design does not consider farmer practices that follow conventional procedures.

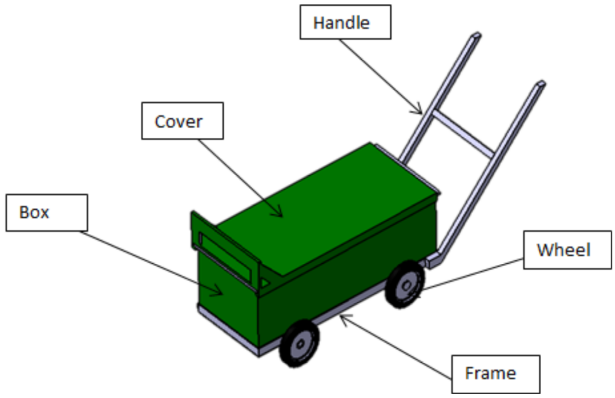

Figure 6. Fermenter box

3.2. Cassava Tuber Processing Technologies

Cassava processing technologies, crucial for increasing shelf life, reducing cyanide content, and improving palatability and involve methods like peeling, grating, pressing, drying, and milling.

3.2.1. Traditional cassava processing tools

Traditional cassava processing in Africa primarily relies on tools like perforated metal sheets, cassava grinders, pestles, hoes, shovels, and mortars for milling and locally made sieves, with minimal reliance on improved technologies.

3.2.2. Mechanical cassava processing technologies

Mechanical cassava processing technologies encompass machines and techniques for tasks like peeling, grating, chipping, and dewatering, which can improve efficiency and increase the demand for cassava in rural areas. The most common cassava processing technologies are peeling, slicing, and grating.

Electrical motor-operated cassava peeler: Cassava peeling machine (Figure 7) has been developed by Mekonnen & Wako (2021, unpublished). It consists of a drum, speed-reducing gear, a set of pulley arrangements. It works on the principles of abrasion. The maximum throughput capacity of 120 kg h^{-1} was recorded at 20% drum fill, independent of drum speed (Mekonnen & Wako, 2021, unpublished). The maximum tuber flesh loss of 7.8%, on the other hand, was recorded when the drum speed was 60 rpm and the drum was filled at 10%. The maximum peeling efficiency of 74.87% of developed cassava peeling machines was recorded when the machine was operated at 60 rpm drum speed, 10% drum fill, and 7 minutes' retention time. The review indicated that this peeler requires improvement to optimize its efficiency and output. Additionally, it is preferable to scale out to end users, as farmers in cassava-growing areas in Ethiopia do not currently use any peeling machines.

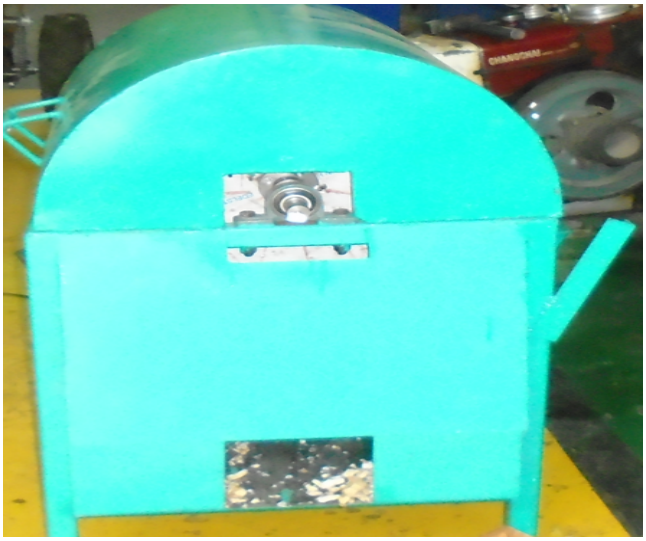

Figure 7. Cassava peeler

Manually operated cassava slicer: This manual cassava slicer was developed by the Melkassa Agricultural Research Centre, Agricultural Engineering research department. According to the evaluation results, the machine's capacity, material loss, and slicing efficiency for cassava were 81.4 kg h-1, 20%, and 73.6%, respectively (Kebede *et al*., 2022, unpublished). It can slice cassava at a thickness range of 1.5 to 3 mm. Because of the irregular shape of the cassava, the circular feeding parts are uncomfortable for feeding the tubers and should be improved. The slices are trapped by the inside chamfered frame components, creating a pile. To make it easier for the slices to flow to the collection box, this section has to be improved.

Figure 8. Manually operated slicers

Combined cassava slicer and grater: This motorized combined machine was developed by Temam (2020) and was less efficient for processing cassava. It could grate 114.94 kg of cassava per hour with a fuel consumption of 325 ml and chip 30.3 kg of cassava per hour with a fuel consumption of 150 ml. This machine performed a very poor job of grating and chipping the cassava tuber. Farmers would be better off using other efficient machines because this one is ineffective at processing cassava due to improperly designed machine components.

Figure 9. Combined cassava grater and slicer

Electrical motor-driven cassava slicer : The cassava slicing machine has been developed by Girma *et al*. (2023). It is powered by a 2.5-hp single-phase electrical motor. The developed cassava slicing machine indicated a slicing capacity of 982.45 kg h^{-1}, a slicing efficiency of 87%, and damaged slices at 9.78% at a slicing disc speed of 500 rpm and a feed rate of 11 kg min^{-1}. The impact of speed on slicing capacity, efficiency, and damage was significant based on the results obtained. From the review, developing this cassava-slicing machine is a significant step towards improving cassava processing by addressing postharvest challenges in cassava-growing areas. This machine required intervention to be scaled out and distributed to end users for chopping instead of slicing.

Figure 10. Electrical motor-driven cassava slicer.

Engine-operated cassava grater: This grating machine was developed by Erchafo (2024a); a test of this grater can be carried out at a moisture content of 54.6% on a wet basis. The test results showed that the operating speed of 28.27 m s^{-1} achieved the maximum grating capacity with a mean of 386.2 kg h^{-1}, followed by 26.18 m s^{-1} and 21.99 m s^{-1}, which achieved a grating capacity of 341.6 and 248.5 kg h^{-1}, respectively. It was also observed that the operating speeds of 28.27 m s^{-1} achieved the maximum grating efficiency with a mean of 97.1%, followed by 26.18 m s^{-1} and 21.99 m s^{-1}, which achieved the grating efficiency of 94.9% and 87.9%, respectively. This cassava grating machine was accessible to farmers who grow cassava, featuring a minor improved grating unit for the effective processing of cassava tubers. Additionally, it is advisable to conduct a participatory evaluation to raise awareness among end users.

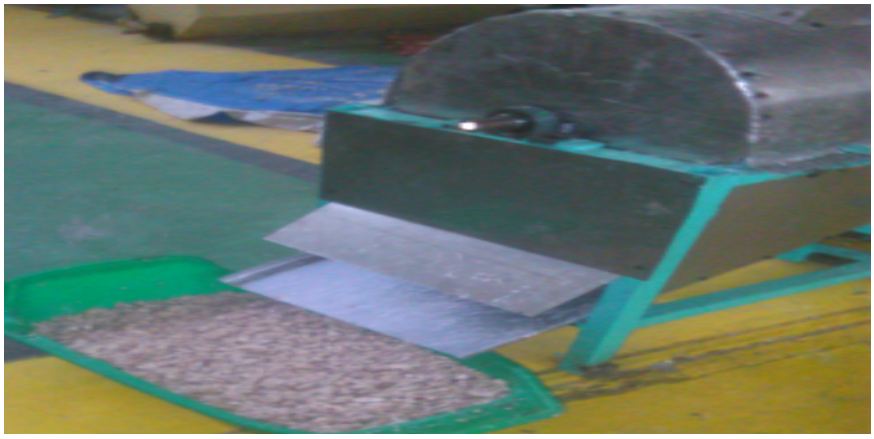

Figure 11. Engine-operated cassava grater

3.3 Potato Processing Technologies

Potato processing technologies encompass various methods and equipment used to transform raw potatoes into a wide array of products, including fries, chips, starch, and more, utilizing techniques such as pulsed electric field, optical sorting, and robotic handling to enhance efficiency and quality.

3.3.1. Traditional potato processing tools

Traditional potato processing tools often include simple manual methods like hand-peeling, slicing with knives or mandolins, and using a potato ricer or press for mashed potatoes.

3.3.2. Mechanical potato processing technologies

Mechanical potato processing technologies encompass a range of methods, including cleaning, peeling, sorting, cutting, grading, washing, blanching, slicing, and various forms of processing to create products like fries, chips, and starch.

Power-driven potato peeler: The potato peeling machine consists of seven parts: the main frame, the peeling drum, the hopper, the collection basin, the waste remover, the water supply system, and the power transmission. The optimum peeling efficiency of 52.55%, 87.99%, and 98% was obtained at 10, 15, and 20 seconds, respectively, and at the recommended drum speed of 1440 rpm. The average value of the mean field capacity of the potato peeler obtained from the trials for small, medium, large, and mixed sizes were 0.092 kg s^{-1}, 0.093 kg s^{-1}, 0.091 kg $s^{-1,}$ and 0.093 kg s^{-1}, respectively. Generally, the mean capacity of the potato peeler obtained from the trials for small, medium, large and mixed sizes were 333.7164 kg h^{-1} (Mohammed, 2017). This peeler can be used on a small scale, so intervention for its use is not very important.

3.4. Turmeric Processing Technologies

Turmeric processing technologies encompass the various methods and techniques used to transform fresh turmeric rhizomes into marketable products. Mechanical turmeric processing technologies employ various machines, including washing, peeling, slicing, boiling, polishing, extraction, drying and grinding, all aimed at enhancing quality and shelf life.

Electric motor-driven turmeric slicing machine: This turmeric slicing machine is powered by a three-horsepower electric motor. From the test results, at 500 rpm speed and 10 kg min^{-1} feeding rates, the maximum slicing capacity of 824.7 kg h^{-1} was recorded; at 300 rpm speed and 15 kg min^{-1} feeding rates, the minimum slicing capacity was recorded. At 500 rpm of speed and 15 kg min^{-1} of feeding rate, a maximum slicing efficiency of 97.4% was found, while at 300 rpm and 10 kg min^{-1} feeding rate, a minimum slicing efficiency of 93.9% was noted. For this machine, the material loss ranged from 4.06 to 7.6% (Erchafo, 2024b). The overall status indicated that this slicing machine is simple to use, requires only one or two people to run, and is easy to make use of. This turmeric slicing machine is highly recommended because, according to test findings, it performed incredibly well when it came to slicing the turmeric rhizome. So this machine needs the intervention of participatory evaluation, scaling out and distributing to end users.

Figure 12. Turmeric slicer

Turmeric polishing machine: This polishing machine for turmeric was considered on the basis of different engineering inputs like the rpm of the motor, the capacity of the polishing drum, feed rates, and the speed of the polishing drum. The performance of the polishing machine was tested at three different capacities, 8, 10, and 12 kg, and three speeds, 45, 60, and 90 rpm. At a speed of 60 rpm and 8 kg capacity, the highest polishing percentage is obtained, which is 7.68% (Dawudi *et al*., 2023, unpublished). The polishing capacity is high compared to hand polishing, 30 kg per hour. The polishing

machine is easy to operate and useful on the farm. So, machine polishing is recommended for raw turmeric processing.

Figure 13. Turmeric polishing machine

3.5. Carrot Processing Technologies

Carrot processing technologies encompass various methods to extend shelf life, enhance nutritional value, and create diverse products, including drying, canning, freezing, and juice extraction, with emerging technologies focusing on preserving quality and functionality.

3.5.1. Traditional carrot processing tools

Traditional carrot processing methods, while simple, often lead to reduced quality, shelf life, and nutritional value due to heat, mechanical damage, and microbial growth, impacting market value and consumer acceptance.

3.5.2. Mechanical carrot processing technologies

Mechanical carrot processing technologies involve using machinery and processes to transform carrots from raw root vegetables into various forms, including washing, peeling, cutting, grading, drying and packaging, often for consumption or further processing.

Power-operated carrot slicer : This carrot slicer machine was driven by a 3.7 kW motor that revolves at a continuous machine speed. From the test results, the maximum capacity of 621.4 kg h^{-1} was recorded at 550 rpm speed, while the minimum capacity of 511.6 kg h^{-1} was recorded at 350 rpm speed. It has been found that the maximum efficiency was 96.03% at 550 rpm speed, whereas the minimum efficiency was 92.5% at 350 rpm speed. For this slicer, the percentage of loss ranged from 4.2 to 7.8 at the above speed range (Erchafo, 2025). This carrot slicer machine's user-friendly mechanism makes it a good option for farmers who cultivate carrots as a vegetable

crop. From the test results, this carrot-slicing machine was found to be highly efficient in processing carrots for end-users.

Figure 14. Carrot slicer

Carrot washing and grading machine: The pedal-operated carrot washing and grading machine was developed by Jarso & Wako (2023). This machine was tested at two levels of feeding loads, 10 kg and 15 kg, at different drum speeds: 70 rpm, 100 rpm, and 140 rpm. The overall mean results obtained for performance indicators in terms of time required to complete washing and grading operations, washing efficiency, grading efficiency, percentage of damaged root, and capacity were recorded as 2.22 min, 98.70%, 92.23%, 1.21%, and 242.17 kg h^{-1}, respectively. From the review, it is recommended that the pedal turning mechanism be altered to perform the dual purpose of producing power that might be stored while in use and utilised at night to improve rural electrification for carrot processing. This machine is better to be motorized rather than pedalled as an intervention for reducing workload for farmers.

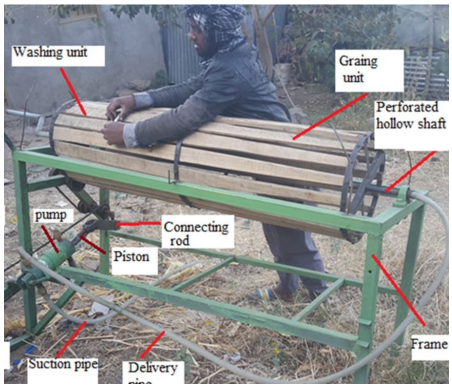

Figure 15. Carrot washing and grading machine

Overall, there is limited postharvest technologies to streamline root crop processing procedures and cut down on labour-intensive tasks and time commitments. However,

various institutions, including Adama, Wolkite, Haramaya, and Ambo universities, as well as Melkassa, Jimma, and the Bako Agricultural Research Centre, have been working on developing postharvest technologies for root crops that would decrease the amount of time and effort required for processing. For example, Bako Agricultural Research Centre has made significant strides in enset as an excellence centre, and Melkassa Agricultural Research Centre has made good progress in cassava. In order to change the livelihood of the farmers and to make it cost-effective, the concerned body has to introduce and scale up the technologies that better perform the tasks for the farmers as they are now in the hands of different institutions. A comprehensive strategy that encourages the use of post-harvest technology while paying particular attention to institutional support structures could minimise post-harvest losses of root crops.

4. Conclusion and Recommendations

Root crops are the most perishable crop, which can deteriorate within two or three days after harvesting, so the intervention of technologies is very important for processing. The review showed there is still a high demand for postharvest technologies to streamline root crop processing procedures and cut down on labour-intensive tasks and time commitments. This study suggests that researchers, institutions, and all stakeholders should explore innovative technologies to address the problem of root crop processing technologies. Based on the current review , the effective technologies that were identified are engine-driven corm grating machine, electric motor-driven cassava slicer, electric motor-driven turmeric slicer, and power-operated carrot slicer machine. These are recommended for intervention with minor improvement, participatory evaluation, scale-up up and distribution for end users.

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Molecular Detection and Antimicrobial Susceptibility Profiles of Listeria Monocytogenes and Other Listeria Species from Cattle Meat in Selected Areas of Eastern Ethiopia

Jelalu Kemal*, Abe Kebede, and Dinaol Belina

Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia
*Corresponding author: jelaluk@gmail.com

Abstract

A cross-sectional study was conducted to molecularly detect, assess factors for contamination of meat, and determine antimicrobial susceptibility profiles of Listeria monocytogenes from beef meat in selected areas of eastern Ethiopia. A total of 470 cattle meat and meat contact surface samples were collected from abattoirs and butchery. Listeria species were isolated using ISO standard techniques. DNA was extracted from Listeria isolates and PCR confirmation of Listeria species and L. monocytogenes was conducted using iap and lmo2234 specific genes primer, respectively. The antimicrobial susceptibility test was done using disk diffusion method. From a total of 470 samples, 29.8% (N=140) were found Listeria species positive. The prevalence of Listeria species identified was 32% (N=98), and 25.6% (N=42) from abattoirs and butcher shops, respectively. Listeria monocytogenes was determined to be 6.4%. Out of 30 L. monocytogenes isolates, 93.3%, 93.3%, and 90% were susceptible to gentamicin, amikacin and kanamycin, respectively. Listeria monocytogenes isolates were 100% and 86.6% resistance to penicillin and tetracycline, respectively. All of L. monocytogenes isolates were multi-drug resistant. The hygienic practices in the abattoirs and butcher shops were found poor. The study showed that there was a widespread of Listeria species and L. monocytogenes in the areas. The finding showed multidrug resistance L. monocytogenes to high number of antimicrobials. Therefore, preventive measures to avoid the presence of L. monocytogenes in meat, emphasizing the need for improved hygienic practices in the abattoirs and butcher shops, appropriate use of drug regulations in humans and animals, and further molecular studies are recommended.

Keywords: Abattoir, multi-drug, PCR, Resistance, Raw meat

1. Introduction

The genus *Listeria* is a Gram positive, non-spore forming and facultative anaerobic bacteria. It comprises more than twenty recognized species, in which *Listeria monocytogenes* represents the only pathogen of public health importance. *Listeria ivanovii* is pathogenic to animals, predominantly in ruminants and has rarely been implicated with human infections. *Listeria monocytogenes* is an intracellular pathogenic bacterium with widespread presence in nature, affecting a wide range of domestic and wild animals and humans (Orsi and Wiedmann, 2016).

Listeriosis is one of the important emerging bacterial zoonotic diseases that occur mainly from the consumption of contaminated food products by *L. monocytogenes* (Amajoud *et al*., 2018). High-risk food items associated with listeriosis include ready-to-eat foods include raw meat and milk (Abay *et al*., 2017). In contrast to most food borne pathogens which mainly cause self-limiting gastroenteritis, *L. monocytogenes* in high-risk groups may cause invasive disease with severe illnesses (Amajoud *et al*., 2018). Certain populations including the pregnant women, the elderly, neonates and immune-compromised individuals are most at risk of sustaining an invasive *L. monocytogenes* infection (Gebremedhin *et al*., 2021). Antimicrobial resistance (AMR) is a global public health concern. There is also growing concern about the transmission of multiple antimicrobial resistant bacteria through the food chain. The increased use of antimicrobial agents in food animal production for treatment and as growth promotion and in humans is a significant factor in the emergence of AMR bacteria and multi drug resistant strains.

In Ethiopia, there is widespread habit and practice of consumption of raw cattle meat and its product (Gebremedhin *et al.,* 2021). Moreover, there is high risk of microbial contamination of raw meat as production, handling and processing of animal products are carried out under poor hygienic conditions. This may be due to lack of knowledge on microbial risks associated with production and handling, absence or inefficient food safety management systems, lack of regulations and regulatory standards (Mulu and Pal, 2016). In Ethiopia, there are also indications on the misuse of antimicrobials by health care providers, unskilled practitioners, and drug consumers. There is inadequate information regarding the prevalence and antimicrobial susceptibility patterns of *L. monocytogenes* and *Listeria* species from cattle meat especially in the eastern part of Ethiopia as most of those studies were conducted in the central part of Ethiopia and limited to culture-based detection and biochemical tests. Thus, identification and antibiotic susceptibility testing of the isolates from cattle meat and meat contact surfaces is helpful for risk assessment and may help better understand about *L. monocytogenes* and other *Listeria spp*. The general objective of this study was to investigate the occurrence, risk factors associated with microbial contamination, molecular detection and antimicrobial susceptibility patterns of *L. monocytogenes* and other *Listeria* species from raw cattle meat and meat contact surface in selected areas of eastern Ethiopia.

2. Materials and Methods

2.1. Study Area Description

The study was carried out in selected areas of eastern Ethiopia viz: Harar, Haramaya and Aweday. Harar town is found 526 km east of Addis Ababa. The town has latitude and longitude of 9°24'N and 42°01'E coordinates, respectively with the altitude range from 1300 to 2200m above sea level. Haramaya and Aweday towns are located at about 495 km and 505 km respectively east of Addis Ababa on the Ethiopian main road from Addis Ababa to Harar town. Haramaya district is topographically situated at an

altitude of 1600 to 2100 above sea level at 9°26'N latitude and 42°3'E longitudes with the mean annual temperature and relative humidity of 18°C and 68%, respectively. Haramaya district receives an average annual rain fall of approximately 900 mm, with a bimodal distribution pattern. The rainfall of the district is bimodal, the short rain occurring between months of February to May. The mean annual rain fall is 492 mm ranging from 118 - 866 mm. The mean maximum and minimum temperatures are 23.4°C and 9°C, respectively (HADB, 2016). The animals slaughtered at all study area abattoirs are cattle, sheep, goat and camel. (Figure 1).

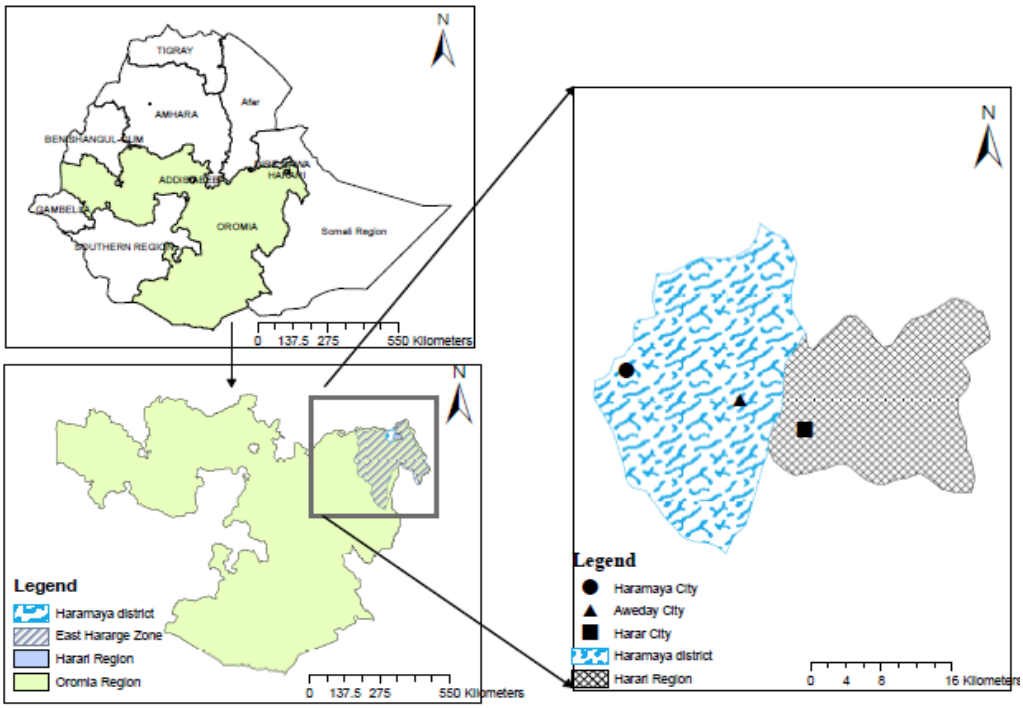

Figure 1: Map of the study areas

2.2. Study Design and Origin of Samples

A cross-sectional study was conducted between August 2023 and March 2024, to investigate the occurrence of *L. monocytogenes* and others *Listeria* species. First, list of all the abattoirs and legal butcher shops found in the areas were registered that was obtained from the towns' municipality (as primary sampling frame) then the four existing abattoirs and five butcher shops from each town were identified. On each sampling day, all the required samples (cattle meat sample, knives, cutting tables, and hooks swabs samples) were taken into consideration. The meat sample was collected from cattle meat from abattoir and butcher shops in the towns. Furthermore, swab samples were collected from equipment's like knives, cutting tables or cutting boards and hooks.

2.3. Sample Size Determination

The approximate sample size required was determined, according to formula described by Thrusfield. (2005).

$$n = \frac{(1.96^2 \text{Pexp}\ (1 - \text{Pexp})}{\text{d}^2}$$

Where n = sample size, Pexp = Expected prevalence, and d = desired absolute precision.

An estimated prevalence of 30% in meat samples from previous studies conducted in central Ethiopia and a confidence interval of 95% and 5% absolute precision were taken for sample size determination (Seyoum *et al.,* 2015). As result, 322 samples were calculated. However, it was inflated to 470 total samples consisting of 306 samples from abattoirs and 164 from butcher shops to increase the precision.

2.4. Sampling Techniques and Processing

Cattle carcasses in the abattoirs were chosen in a systematic random sampling method and examined just after the stage of evisceration. For the butcher shops, convincing or purposive sampling approach was performed, and the samples were taken from the sites where they were sold to the consumers. Twenty-five grams of meat was randomly collected aseptically using sterile plastic bags/containers. The abdomen (flank), thorax (lateral), crutch, breast (lateral), which are sites with the highest rate of contamination were chosen for sampling. The selected meat contact surface samples were swabbed aseptically using the method described in (ISO11290-1996), by placing sterile template (10 x 10 cm) from equipment like knives, cutting tables or cutting boards and hooks. All samples were collected aseptically using sterile plastic bags, labeled, and transported to veterinary microbiology laboratory. During sample collection, demographic data from abattoir personnel, butcher shop workers were collected. The meat samples were processed according to the protocol (ISO 11290-1: 2018).

2.5. Isolation of *Listeria* Species

For isolations of *Listeria,* the primary and secondary enrichment media were used. Accordingly, 25 g of sample was homogenized in 225 ml (one to nine proportion) in half Frazer both (Demi-frazer both, Difco, sparks, USA) containing supplements using stomacker bags. Hence, 0.1 ml of a growth suspension were taken from the overnight incubated primary enrichment broth (Half frazer both/Demi-frazer) and transferred into full Fraser Broth medium followed by incubation for 24 to 48 h at 37°C. For cattle meat surface contact each sample unit which was kept in buffered peptone water was mixed thoroughly to ensure the homogeneity of its contents and about 0.1 ml unit was obtained aseptically in to 10ml of half Frazer both containing supplements, followed by mixing and the sample was kept inside incubator and incubated at 37^{o}C for 24 hr. Presumptive *Listeria* colonies around them on PALCAM agar was streaked onto the surface of pre-dried plates of Tryptone Soya Yeast Extract Agar (TSYEA) and incubated

at 37°C for 24 hr. Typical colonies which are 1 mm to 2 mm in diameter, convex, colorless and opaque was used for further confirmation biochemical tests (ISO 11290-1, 1996) and stored at -20°C in BRI broth with 20% glycerol.

2.6. Molecular Detection of *Listeria monocytogenes*

2.6.1. DNA extraction

DNA was extracted from recovered presumptive *Listeria* isolates by boiling method as described in Mehrez *et al*. (2009). Briefly, a visible mass from a well isolated colony on BHI agar was picked using a loop and suspended in 100 µl of nuclease free water in micro centrifuge tubes and vortexed for 30 seconds. Then, the suspension was heated to 95-100°C on thermal block for 10 minutes and cooled down for 2 minutes at room temperature. Then, the suspension was centrifuged at 14,000 rpm for 5 minutes. Then, 50 µl of the supernatant was carefully transferred to a new micro centrifuge tubes and used as a DNA template for PCR amplification of *Listeria* species and *Listeria monocytogenes* (Mehrez *et al*. 2009).

2.6.2. PCR confirmation *Listeria* species and *Listeria monocytogenes*

Polymerase chain reaction (PCR) confirmation of *Listeria* species and *Listeria monocytogenes* was conducted using specific *Listeria* genus primers using iap (invasion associated protein) and lmo2234 genes, respectively based on Chen and Knabel (2007). The PCR reaction was conducted in 25 µl reaction mixtures with an initial activation step for 8 min at 95°C followed by 34 cycles of 1 min at 94°C, 1 min at 54°C and 1 min at 72°C and a final extension at 72°C for 8 min. The reaction mixture of PCR amplification used for identification of *Listeria* species consisted of 12.5 µl of GoTaq Green master mix (ready to use), 0.875µl of each *iap* forward and *iap* reverse primers (for *Listeria* species) and 1.5 µl of each of lmo2234 forward and lmo2234 reverse primers (for *L. monocytogenes*) (Table 1), 8.25µl of nuclease free water (7µl for *Listeria monocytogenes*) and 2.5 µl of DNA template, giving a total volume of 25 µl. The resultant PCR product (7 µl) was loaded and electrophoresed in 1.5% agarose gel in 1X TAE (Tris-acetic acid EDTA) buffer stained with gel red (10 mg/ml) for 40 minutes at 100V. DNA bands of the ladder and PCR products were visualized and photographed using a UV trans-illuminator. Band views of 420 and 1,450-1,600 base pairs (bps) were used to determine isolates as *Listeria monocytogenes* and *Listeria species*, respectively (Figure 2-5)

Table.1: Gene target, primer sequence, expected amplicon size of *Listeria* species and *Listeria monocytognes* PCR

Gene target	Isolate group	Primer sequence	Amplicon size (bp)
lmo2234	*L. monocytogenes*	(F) TGTCCAGTTCCATTTTTAACT (R) TTGTTGTTCTGCTGTACGA	420

Iap	*Listeria* spp.	(F) ATGAATATGAAAAAAGCAAC (R) TTATACGCGACCGAAGCCAAC	1,450–1,600

F: Forward Primer sequence, R: Reverse Primer sequence

2.7. Antimicrobial Susceptibility Testing

The *Listeria monocytogenes* isolates were subjected to an antimicrobial susceptibility test against thirteen (13) commercially available antimicrobial discs (Oxoid, UK) which were selected based on common usage namely: Penicillin (P10 µg), Amikacin (AMK30 µg), Amoxicillin (AML20 µg), sulfamethoxazole/trimethoprime (SXT 25 µg), Cephalothin (KF 30 µg), Vancomycin (VA 30 µg), Gentamicin (CN 10 µg), Tetracycline (TE 30 µg), Kanamaycin (K30 µg), Streptomycin (ST 10 µg), Oxacillin (30 µg), ciprofloxacin (6 µg) and Choloraphenicol (C30 µg). Disk diffusion method, using Kirby-Bauer technique was applied by 0.5 McFarland Standard (CLSI, 2005).

2.8. Survey Questionnaire

A structured questionnaire was prepared to assess the knowledge of workers in abattoir and butcher shops regarding the hygienic and sanitary practices during slaughter and processing of meat. Demographic data from abattoir personnel and butcher shop workers were collected including the sex, the residence of origin, educational status, and work experience in years. Besides, an observation was made on the hygiene of the abattoirs, cutting boards, food handling surfaces, and of butchers. Simultaneously, observational study of the municipal abattoir and butcher shops was undertaken during the study period. All study subjects were informed about the study and confidentiality of the information was maintained throughout the study. A structured questionnaire was prepared for 35 butcher shops and 65 abattoir workers.

2.9. Data Quality Control

Positive and negative controls were used for quality assurance of data generated by different sub typing methods. *Listeria monocytogenes* (ATCC 35152), (CDC 91116) and (ATCC 19116) reference strains were used as positive controls. All control strains were from Ethiopia Public Health Institute (EPHI).

2.10. Data Management and Analysis

The data were entered into Microsoft Excel spreadsheets and analyzed using STATA version 13 software. Descriptive statistics was used to summarize the occurrence, and antimicrobial susceptibility data. The diameters of the zones of inhibition were recorded. Chi-square test analysis was used to determine whether there is a significant difference in the occurrence of *Listeria* species in different sources of the samples, study area and types of samples. Differences were considered significant for *P* values less than 0.05. Logistic regression analyses with their Odds Ratio (OR) and 95%

confidence Intervals (95% CI) were used to determine potential risk factors associated with meat contamination by *Listeria* species.

3. Result and Discussions

3.1. The Overall Occurrence of *Listeria* Species

From the total 470 samples taken for investigations of *Listeria* species using culture and biochemical tests, 29.8% (N=140) were found positive. Out of total samples collected, 32% (N=98) and 25.6% (N=42) were positive for *Listeria* from samples originated from abattoirs and butcher shops, respectively (Table 2). Of the total samples, the occurrence of *Listeria* species in meat contact surface equipment was lower than raw meat samples. The result was higher in raw meat samples among different sample types; with no significance difference in prevalence ($p>0.05$) (Table. 3). The highest *Listeria* species prevalence was recorded in Haramaya town (31.6%) followed by Haramaya University (31.3%) while the least prevalence of *Listeria* species was recorded in Harar town (24.7%) (Table 4).

Table 2: Prevalence of *Listeria Species* in cattle meat samples obtained from abattoir and butcher shops from selected area of eastern Ethiopia.

Sample Source	No. Examined	Positive (%)	OR	95% CI	P-value
Abattoirs	306	98 (32%)	1.0	1	-
Butcher shops	164	42 (25.6%)	1.37	0.9-2.1	0.17
Total	470	140 (29.8%)			

Table 3: The prevalence of *Listeria* species from different types of samples from selected areas of eastern Ethiopia

Sample Types	No. Examined	Positive (%)	OR	95% CI	P-value)
Raw meat	405	127 (31.6%)	1.0	1	-
Knife	25	6 (24%)	1.45	0.56-3.7	0.43
Cutting broad	25	6 (24%)	1.45	0.57-3.7	0.44
Hook	15	1 (6%)	6.4	0.83-49.3	0.074
Total	470	140 (29.8%)			

Table 4: Overall prevalence *Listeria* species in different study area.

Study area	No. Examined	Positive (%)	OR	95% CI	P-value
Haramaya	190	60 (31.6)	1.0	1	-
Aweday	115	34 (29.6)	1.68	0.67-1.83	0.69
Haramaya University	80	25 (31.3)	1.14	0.58-1.79	0.94
Harar	85	21 (24.7)	1.42	0.79-2.53	0.24
Total	470	140 (29.8)			

3.2. Prevalence of *Listeria monocytogenes* and Others *Listeria* Species

The overall prevalence of *L. monocytogenes* was 6.4% (N=30). The percentage of *L. monocytogenes* in abattoirs and butchers in the study area were 23 (7.5%) and 7 (4.3%), respectively (Table. 5).

Table 5: Distribution of *Listeria* species isolated from abattoirs and butcher shops.

Listeria Species Isolated	Samples Sources			
	Abattoirs	Butcher shops	Total (%)	χ^2 (P-value)
L. monocytogenes	23	7	30 (6.4%)	5.18 (0.64)
L. inanovi	11	3	14 (2.9%)	
L. grayi	20	8	28 (6%)	
L. seeligeri	6	3	9 (1.9%)	
L. innocua	20	13	33 (7%)	
L. welshimeri	8	2	10 (2.1%)	
Others Listeria species	12	7	19 (4%)	
Total	98	42	140 (29.8%)	

3.3. PCR Confirmation of *Listeria* Species Isolates

The phenotypically and biochemically characterized *L. monocytogenes* were also molecularly confirmed as *L. monocytogenes* using specific *Listeria* genus primers using iap (invasion associated protein) genes. Of the total 40 *Listeria* isolates examined for PCR confirmation, ten were confirmed as *L. monocytogenes* (Figure 2, 4), while eight isolates of other *Listeria* species (Figure 3, 5) were identified in the PCR.

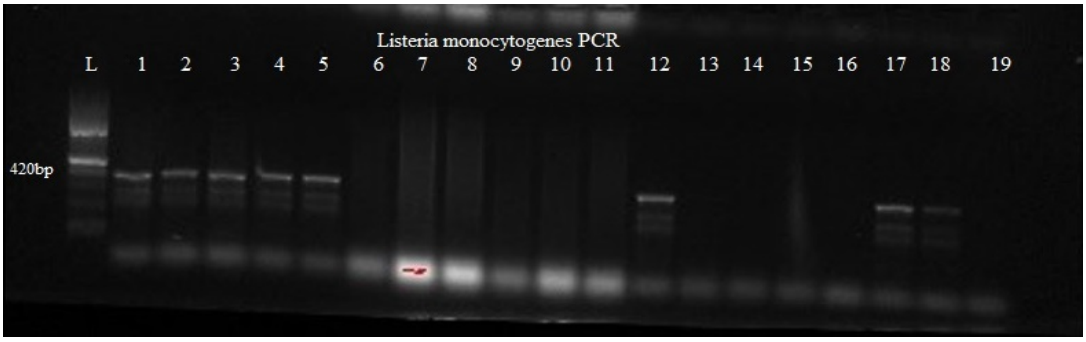

Figure 2: Gel electrophoretic profile of PCR for *lmo2234*gene in *L. monocytogenes* isolates

Key: 1: 100bp DNA ladder; 2: HARF5 (+ve); 3: HARB11 (+ve); 4: AB9 (+ve); 5HARB-16 (+ve); 6: HARB-C1 (-ve); 7: AM16-C2 (-ve); 8: AM23 (-ve); 9: HM8 (-ve); 10: HM53 (-ve); 11: HM42 (-ve); 12: AB16 (+ve); 13: HARB1 (-ve); 14: HARB9 (-ve): 15: HARB7 (-ve); 16: HB92 (-ve); 17: HARCB9 (+ve); 18: positive control; 19: negative control.

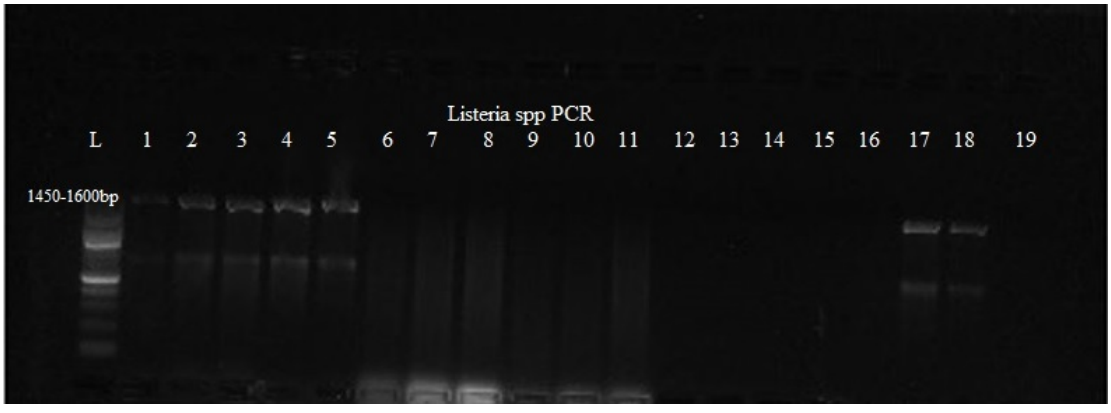

Figure 3: Gel electrophoretic profile of PCR for *iap*gene in *Listeria* species isolates

Key: 1: 100bp DNA ladder; 2,3,4,5,17: positive; 6-16: negative; 18: positive control; 19: negative control.

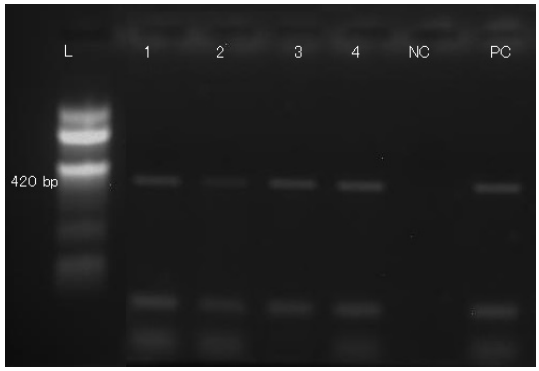

Figure 4: Electrophoretic profile of PCR for lmo2234 gene in *L. monocytogenes* isolates

Key: Samples 1-4 are positive for *Listeria monocytogenes* (show band at 420 bp). NC = negative control and PC positive control

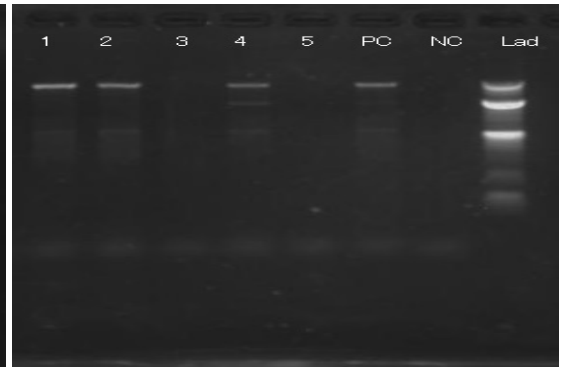

Figure 5: Gel electrophoretic profile of PCR for *iap* gene in *Lesteria* spp.isolates

Key: Samples 1. 2 and 4 are *Listeria* spp positive, Samples 3 and 5 are *Listeria* spp negative; PC positive control; NC negative control; Lad= 100 bp ladder. *Listeria* spp show bands between 1450 and 1600 bp

3.4. Antimicrobial Susceptibility Profile of *Listeria monocytogenes* Isolates

Out of total 30 *L. monocytogenes* subjected for antimicrobial susceptibility test; all the isolates (100%) were exhibited resistance for penicillin G. Out of total *L. monocytogenes* isolates 26 (86.7%) were resistant to tetracycline. Twenty-four isolates (80%) of *L. monocytogenes* were equally resistant to amoxicillin and cephalothin. The highest percentage 28 (93.3%) of the isolates were equally susceptible to amikacin (93.3%) and gentamaycin (93.3%) followed by kanamaycin 27 (90%) (Table 6).

Table 6: Results of the Antimicrobials Patterns of *Listeria monocytogenes* Isolates (N=30) from Raw Cattle Meat Samples of the Abattoirs and Butcher shops.

Antimicrobial	Disc potency (μg/disc)	Number of isolates	Susceptible N%	Intermediate N%	Resistance N%
Penicillin G	10	30	0(0%)	0(0%)	30(100%)
Amikacin	30	30	28(93.3%)	2(6.67%)	0(0%)
Amoxicillin	20	30	2(6.67%)	4(13.3%)	24(80%)
Sulfamethoprime	25	30	0(0%)	18(60%)	12(40%)
Cephalothin	30	30	1(1.3%)	5(16.7%)	24(80%)
Vancomycin	30	30	3(10%)	5(16.7%)	22(73.3%)
Gentamicin	10	30	28(93.3%)	1(1.3%)	1(1.3%)
Tetracycline	30	30	0(0%)	4(13.3%)	26(86.7%)

Kanamaycin	30	30	27(90%)	3(10%)	0(0%)
Streptomycin	10	30	3(10%)	4(46.7%)	13(43.3%)
Oxacillin	30	30	1(1.3%)	6(20%)	23(76.7%)
Ciprofloxacin	6	30	12(40%)	9(30%)	9(30%)
Chloramphenicol	30	30	3(10%)	13(43.3%)	14(46.7%)

The result in this finding indicated significant public health hazard associated with consumption of contaminated raw cattle meat with *L. monocytogenes*. The prevalence of *Listeria* species from raw cattle meat and meat surface contact in the present study agreed with the work of Gebremedhin *et al.* (2021) who reported 28.4% *Listeria* species isolated in beef cattle from abattoirs, restaurants and butchers' shops in Ambo and Holeta. The contamination of knife, hook and cutting table with *Listeria* species in our study is found higher than Mulu and Pal (2016) who report 6.7% of prevalence of *L. monocytogenes* from sheep meat contact surface materials. This might be due the absence of hot water and sterilizer to sterilize the materials.

The level of contamination by *L. monocytogenes* and *L. seeligeri* obtained in this study was similar with the study by Garedew *et al.,* (2015) who reported 6.25% and 1.3%, respectively, from ready-to-eat foods of animal origin in Gondar town. However, the present study is lower than the study by Molla *et al.* (2004) who reported 15.5% and 8.7% *L. monocytogenes* and *L. seeligeri,* respectively in Addis Ababa. These differences may depend on geographic location, sampling technique, sampling populations and types and sample sources hygienic production (Jami *et al*., 2011). The high level of carcass contamination with *L. monocytogenes* is of special public health significance in developing country like Ethiopia, where raw and under cooked meat is the favorite food in most areas (Molla *et al*., 2004).

The 100% resistance level in this study for penicillin G is similar with the finding of Bushura and Addis (2020) who reported 100% resistant to *Listeria* species to penicillin from food sample at Haramaya University. The hundred percent resistant *L. monocytogenes* isolates to penicillin in current finding might be due to high level utilization of this antibiotic or its relatively cheaper price and readily available nature to the local community. Large proportions of the isolates were found to be highly susceptible to gentamicin (93.4%), amikacin (93.3%) and kanamycin (90%). It agrees with the finding of Mulu and Pal (2016) who reported 97.2% *L. monocytogenes* susceptibility to gentamicin. The effectiveness of such drugs could be due to their limited use in countries like Ethiopia and other African countries. Resistance to multiple antimicrobials (100%) is higher than other studies conducted in Ethiopia. This finding is similar with the finding of Bushura and Addis (2020) who reported 100% resistance to one or more antimicrobial.

In the present study majority of abattoir (58%) and butcher shops workers (65.7%) had only enrolled in a primary school education. The results agreed with the finding of Gebremedhin *et al.* (2021) who reported a primary school education of 51.5% and 55.2% from abattoirs and butcher shops workers, respectively. The present study

revealed that most of the abattoir and butcher shop workers had a low level of education. This could make difficult in acceptability of modern slaughtering practices as well as adherence to strict hygienic and standard slaughtering. Among sixty-five abattoirs workers only 6 (9.2%) were washing hands with water and soap but from butcher shops more than 65% of respondents were washing hands with water and soap. There was no hot water, soap, sterilizer and retention room and equipment (knife) rest on dirty surfaces in study abattoirs.

4. Conclusion and Recommendations

The result showed that raw cattle meats are positive for both pathogenic *L. monocytogenes* and others *Listeria* species. The presence of *L. monocytogenes* in meat can pose a threat to human life and can cause outbreaks of listeriosis. *Listeria monocytogenes* isolates showed resistance to commonly used antimicrobials and all isolates exhibited multiple drugs resistant to at least three and more than three antimicrobial classes. High resistance level was recorded to penicillin G, tetracycline, amoxicillin, cephalothin, and oxacillin. The finding also indicates that there is low level of public awareness about contamination of cattle meat with *Listeria* species, and the associated probable risk if the pathogen reaches to ready to eat foods of consumers. The finding also indicates that there are poor hygienic practices in the abattoirs and butcher shops. Effective cleaning and sanitation of abattoirs and butcher shops and creating public awareness through disseminating the information is necessary to combat the problem. Attention must be also given to the habit of consuming raw cattle meat. The prudent use of antimicrobial drugs in veterinary and public health sectors is of a great importance.

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Enhancing Meat Quality in the Ethiopian Livestock: Challenges and Strategies

Birmaduma Gadisa Muleta*[1] and Mulisa Faji Dida[2,3]

[1]Oromia Agricultural Research Institute, Bako Agricultural Research Center, Ethiopia
[2]University of Sydney, School of Life and Environmental Sciences, Australia
[3]Ethiopian Institute of Agricultural Research, Holetta Agricultural Research Center
*Corresponding author email: birmaduga@gmail.com

Abstract

Demands for animal products are rising globally, and Ethiopia possesses significant potential to meet this demand through meat and meat product production for both domestic and international markets. However, the Ethiopian meat industry faces numerous challenges, with a substantial percentage of carcasses from cattle, sheep, and goats being rejected in the international market due to low quality. This review was aimed at highlighting the factors that predispose animals to low-quality meat in Ethiopia. The low quality of meat in Ethiopian livestock stems from a combination of on-farm and off-farm factors. On-farm issues encompass disease, animal nutrition, production systems, age at slaughter, sex, breed, genetics, and management. Off-farm challenges involve stress during transport, in lairage, or at slaughter, including factors such as unusual noise, mixing with unfamiliar animals, overcrowding, beating, vibration, restraint, deprivation of feed and water, adverse weather conditions, fighting in lairage, and stunning. These problems result to dark cutting, tough, bruised, and contaminated meat that leads to total condemnation. Therefore, addressing these challenges requires a multifaceted approach. Humane animal handling and appropriate management practices, along with proper training for abattoir staff and traders, are essential. Establishing disease-free zone, raising awareness among stakeholders about quality standards, and implementing appropriate regulations for transportation and slaughter are also vital steps. By implementing these measures, Ethiopia can enhance the quality of its meat products and better meet the demands of both domestic and international markets.

Keywords: Carcass, Dark Cutting, Pre-slaughter stress

1. Introduction

Ethiopia is home to immense and diversified species of livestock resources due to its diverse agro ecologies. The total cattle, sheep, goats, poultry and camels population of the country is estimated at 70, 42.9, 52.5, 56.87, and camels 8.1 million, respectively (CSA, 2022). However, livestock and livestock products are underutilized compared to their potential as they account for less than 1% of global exports of meat products, mainly mutton and chevon (Eshetu and Abraham, 2016).

In Ethiopia, livestock production for meat purpose is limited to feedlot operations close to urban and peri-urban areas. In rural areas, the availability of concentrate feed is rare

and costly, thus most animals are finished mainly on natural pasture, other forages, and/or crop residues without supplementation. Cattle in Ethiopia are marketed at very old age (> 7 years). Female cattle are often marketed as cull cows and steers are marketed after being used for draught purposes under crop-livestock farming systems (Mummed and Webb, 2015; Gebeyehu, 2013). These practices have contributed to a low level of meat production compared to that of other countries in Eastern Africa (Assefa, 2017). In 2016/17 Ethiopia produced 46,120 tons of meat and exported only 19,105 tons (41.4%) (Addis *et al*., 2019). This is a very low rate of exportation compared to the number of livestock resources of the country. Recently, Ethiopia has been trying to rise from a status of relatively no meat exportation to that of a meat exporter country through building new markets in many Middle Eastern and African countries such as the United Arab Emirates (UAE), Saudi Arabia, Yemen, Jordan, Kuwait, Oman, Qatar, Syria, Angola, Bahrain, and Egypt (Yami *et al.,* 2018) . About 20% of live animals are exported through official channels, and the remaining 80% are traded illegally (FAO, 2019).

Sheep and goats are sent to market without considering their mutton and chevon quality, respectively (Zelealem *et al.,* 2012). The inability to produce high-quality carcasses is one of the major problems facing Ethiopian meat exporters (Mummed and Webb, 2015). Consumers prefer low-fat, packaged, and labelled meat, focusing on a limited number of specific cuts from specific ages and breeds (Yami *et al.,* 2018). Another problem is that the domestic prices for live animals in Ethiopia are higher than those of neighbouring countries (Brasesco *et al.,* 2019). As a result, the meat industry of Ethiopia is uncompetitive in international markets (Yami *et al*., 2018). Therefore, this review highlights the prevailing challenges in Ethiopia's meat industry to ascertain strategies of evidence-based interventions to optimize benefits and unlock the sector's productivity potential.

2. Materials and Methods

This comprehensive narrative review assesses the impacts of livestock production on meat quality, as well as the challenges and strategies a particular focus on production systems and meat darkness. The study used a systematic approach to identify, synthesize, and analyse relevant information from peer-reviewed journals, legal briefs, and reputable indexed databases, including Google Scholar, Web of Science, PubMed, and Scopus. Employing targeted keywords such as "Carcass", "Dark Cutting", "Livestock", "Meat quality", "Pre-slaughter stress" the research ensured a focused and comprehensive literature search. Studies published in the last decade were prioritized, with inclusion criteria emphasizing empirical findings and theoretical insights, while irrelevant studies were excluded. The extracted data were thematically organized into four major key areas: Meat imports and exports in Ethiopia, meat quality defects in Ethiopia, major causes of meat quality defects in Ethiopia, and strategies to minimize meat defects in Ethiopia. A rigorous cross-referencing strategy was applied to validate the findings and ensure their credibility. This review identified systemic inefficiencies

by synthesizing thematic insights and proposed evidence-based strategies for sustainable improvement.

3. Results and Discussion

3.1. Meat imports and exports in Ethiopia

3.1.1. Meat imports

Livestock production systems in Ethiopia are largely subsistence-oriented, and productivity is very low. The market supply of animals originates from highly dispersed, small farms that supply small numbers of nonhomogeneous animals. The animals supplied to the market fall short of meeting the quality attributes required by high-end domestic (HED) and export markets (Yami *et al*., 2018). Hence, Ethiopia remains dependent on meat imports (Table 1) despite some of the products being produced domestically. The country imports various livestock meats and processed products. Total imports grew exponentially at 19% per annum between 2006 and 2016, with import value multiplied by six from 500,000 USD in 2006 to 3 million USD in 2016 (Yami *et al*., 2018). Ethiopia has imported significant amount of meat each year from Italy, China, the USA, the Netherlands, UAE, and South Africa (Mummed and Webb, 2015). The key justification for meat importation from abroad is the lack of high-quality domestic meat for sale to high-end outlets such as hotels and supermarkets where specific taste requirements and cut demands are largely driven by tourists, diplomats, and international events held in the country. These consumers prefer high-quality, low-fat, well-packed, and labelled meat, focusing on a limited number of specific cuts. The most desired cuts include beef topside, sirloin, and tenderloin.

Ethiopian supermarkets mainly sell raw and processed beef (sausages) products directly to consumers (Yami *et al*., 2018). Sadly, this indicates that even the quality of meat produced in Ethiopia is not acceptable to all domestic consumers. Thus, it is not surprising that Ethiopian meat does not compete well in the international market (Addis *et al*., 2019). According to (Yami *et al*., 2018), Ethiopia spends a huge amount of dollars to import meat from different countries. For example, in 2018, 1 kg of fresh beef imported from South Africa cost about 33 USD while 1 kg of local beef cost 10 USD (Eshetie *et al*., 2018). Informal business communication among livestock and multiple value chain actors (Gadisa, 2018) is one of the contributing factors to the fundamental problems of meat quality in Ethiopia. Implementing a recently designed breeding strategy, improved feeding, health service, product safety, product promotion, excellent relationships among industry actors, and conducive management conditions should be a path to market success. Product assurance and integrity are the other two key aspects influencing consumer confidence and retail meat purchasing power in national and international markets (EDMID, 2016).

Table 1. Distribution of types of importers of beef into Ethiopia (2006–2017)

Importers	No. of importers	Frequency of imports	The total value of imports			
			ETB	Share %	USD	Share %

Catering companies	2	49	11,832,309.2	33.0	643,230.4	31.9
Construction companies	24	98	15,843,148.8	44.2	917,528.3	45.4
Embassies	8	25	456,002.6	1.3	28,494.5	1.4
Hotel and restaurants	3	15	1,296,636.4	3.6	68,504.0	3.4
Trading companies	14	74	5,407,052.6	15.1	290,054.9	14.4
Supermarkets	5	27	876,565.6	2.4	63,128.9	3.1
Other organizations	2	2	165,784.5	0.5	7,961.9	0.4

Source: Yami *et al*., 2018

3.1.2. Live animals and carcasses exported from Ethiopia

Meat and live animals are exported from Ethiopia to the Middle East and some African countries (Management Entity, 2021). Annually, over 2.3 million live animals, including cattle, sheep, and goats, are exported both formally and informally (Brasesco *et al*., 2019). Exports of goats and camels from Ethiopia to Somalia were 19 and 47 percent in 2023, which is higher than the five-year before due to better rainfall, improved rangeland, and animal body conditions of the year (FAO, 2024). Chilled/frozen beef, goat meat, mutton, chilled veal, chilled camel meat, and red offal are mainly exported to the United Arab Emirates (UAE), Saudi Arabia, Angola, Egypt, Bahrain, Turkey, and Kuwait. All the exported meat is sold through formal channels, due to regulations of the importing countries. Live animals are exported to Somalia, Kenya, Sudan, Djibouti, Egypt, UAE, Saudi Arabia, and Yemen. Informal cross-border trade mostly consists of live animals (Management Entity, 2021; Yami *et al*., 2018).

Even though Ethiopia has a high potential and opportunity to export live animals to the international market periodically interrupted due to the bans imposed by importing countries (Yami *et al*., 2018). The main causes of bans for meat exporters are disease outbreaks and unsatisfactory product quality (Brasesco *et al*., 2019). Diseases cause huge economic losses to producers and livestock exporters. A dark cutting (DC), contamination, toughness, dryness, fatness, small carcass size, lack of uniformity of the cuts supplied, poor sanitation, inappropriate packing, branding, labelling, and lack of continuous supply of meat have been reported as contributing factors to the failure to meet acceptable international standards (Yami *et al*., 2018). The stress animals undergo before slaughter leads to inadequate meat quality, a primary reason for consumer rejection. Consequently, approximately 80% of live animals are traded illegally (FAO, 2019), and sometimes packaged and sold under the labels of Indian, Pakistani, or Somali meat (Yami *et al*., 2018).

3.2. Meat quality defects in Ethiopia

Meat quality is the major challenge confronting the Ethiopian meat industry. Due to inadequate qualities, most of the carcasses are unfit for export from Ethiopia and are rejected. This problem also makes the country vulnerable and dependent on meat imports. The following sections discusses the factors predisposing animals and meat to defects, along with strategies to minimize such defects in the Ethiopian livestock.

3.2.1. Dark cutting

Dark-cutting meat, mostly known as dark, firm, and dry meat, is described as having a dark, purple red to black color that makes it appear less fresh and undesirable to consumers (Table 2). It is also less tender, has an undesirable flavour, and has a short shelf life. Dark-cutting (DC) meat has been observed in all species (Table 2). Meat color is the most important attribute that influences customers' decisions at the point of purchase (Udomkun *et al*., 2018). Consumers use meat color as an indication of freshness and wholesomeness when purchasing fresh meat at the place of sale (Yami *et al*., 2018). Dark-cutting meat is mainly identified by visual assessment within the visible light spectrum. The color of normal meat which is preferred by most people is bright-red, cherry-red, or pinkish- to bright- red (Ponnampalam *et al*., 2017). Normal muscle blooms to a bright cherry-red color when exposed to air. Deviations in meat color from the bright cherry-red color are defect indicators (Wicks *et al*., 2019).

Another characteristic of DC meat is its dryness and firmness, which is determined by touching the surface of the meat (Table 2). Meat is called DC when the ultimate pH post-mortem, measured after 12 – 48 hours, is greater than 5.9. The ultimate pH of DC ranges from 5.9 to 6.5, with some meat reaching 6.8. These values are higher than the normal pH range (5.4-5.7) of meat from an unstressed animal (Adzitey and Nurul, 2011). Dark-cutting meat can also be defined based on glycolytic potential or glycogen levels in the muscles of slaughtered animals. Muscle glycogen levels at rest should be 0.8 to 1.0 % before slaughter for cattle. Muscle glycogen reserves of an animal subjected to various forms of long-term pre-slaughter stress are significantly low due to depletion (Ponnampalam *et al*., 2017). Decreasing muscle glycogen levels to less than 0.6% limits the production of lactic acid and associated hydrogen ions that are responsible for decreasing the pH of meat (Ponnampalam *et al*., 2017). Thus, a glycogen deficiency would prevent the normal decline of meat post-mortem pH (Addis *et al*., 2019; Adzitey and Nurul, 2011).

A variety of severe pre-slaughter stresses can cause the depletion of muscle glycogen (Miller, 2007). Pre-slaughter stresses change the color of the meat to dark by preserving the structure of a protein called myoglobin, which transports oxygen from the blood to the muscle mitochondria (Walsh *et al*., 2019). If the animal's glycogen is depleted before slaughter, the pH may not drop quickly enough to denature myoglobin. In this case, the meat will be dark in color and have high water-holding capacity as other muscle proteins remain in their native configuration (Warner, 2017).

Dark-cutting meat has a reduced shelf-life and a greater ability to support microbial growth (Table 2). Increased microbial activity leads to more spoilage and the development of an unpleasant flavour. Reduced shelf-life is primarily due to a high pH and capacity to retain water, which is conducive to microbial growth. The problem is related to decreased levels of muscle glycogen, which limits its conversion to lactic acid. Lactic acid bacteria are naturally found on meat and "compete" with spoilage bacteria. The reduction in glycogen results in a significant decrease in lactic acid bacteria. As a result, bacteria that produce hydrogen sulfide, which causes an off-odor and green discoloration, multiply and proliferate (Ponnampalam *et al*., 2017). It has been reported that dark-cut beef consumed before spoilage has a slightly soapy off-flavour (Addis *et al*., 2019). Consumers tend to avoid DC meat due to the perception of the meat being from old, mistreated, stressed, poorly handled, and unhealthy animals (Ponnampalam *et al*., 2017).

Table 2: Summary of indicators of dark-cutting meat

Dark-cutting meat description	**References**
Dark in color	Ekiz *et al*., 2012; Gruber *et al*., 2010; Muchenje, 2009; Warriss, 2000
Low light scattering ability	Warriss, 2000
Dryness and Firmness	Ponnampalam *et al*., 2017
High water holding capacity	Rani *et al*., 2017; Ekiz *et al*., 2012
Abnormal tenderness	Swatland, 2008
Smaller extracellular space	Warriss, 2000
High ultimate pH (>5.8) and lower amino acid due to glycogen depletion pre-slaughter	Ekiz *et al*., 2012 ; Muchenje, 2009; Kannan *et al*., 2001
Spoilage odour is produced at an early age/short microbial shelf life	Gallo *et al*., 2003; Warriss, 2000
High oxygen (O_2) used up due to cytochrome activity	Chulayo & Muchenje, 2013; Warriss, 2000
Increased the level of creatine kinase (CK) and lactate dehydrogenase (LDH) enzyme	Addis *et al*., 2019; Alam *et al*., 2018; Chulayo and Muchenje, 2013

Dark-cutting meat may occur due to many on-farm and off-farm factors. The major on-farm factors that have been related to DC meat are the production system, nutritional background, animal management, breed, sex, age at slaughter, and subclinical diseases (Ponnampalam *et al*., 2017). Off-farm activities include fatigue after transport to market, fear, fighting in lairage, beating, climatic changes, aggressiveness, prolonged withholding of feed before slaughter, mixing of unfamiliar animals, and stunning. These factors can lead to physical, physiological, and psychological changes in the animal body affecting the ultimate quality and profitability of the meat. A review covered in detail, the causes, contributing factors, and mechanism of DC meat in sheep and cattle,

and suggested some future research directions to minimize its incidences (Ponnampalam *et al*., 2017).

As a consequence of pre-slaughter stress, an animal may experience fear, dehydration, hunger, increased physical activity and fatigue, and physical injury. This autonomic response results in the secretion of catecholamines and glucocorticoids. Increased secretion of these hormones amplifies the mobilization of energy sources in the body. Catecholamine clearly invoke significant changes in glucose metabolism, resulting in significant depletion of muscle glycogen reserves (Walsh *et al*., 2019). Glucocorticoids are steroid hormones released in animals in response to both chronic and acute stress. The result significantly affects meat quality through suppressing muscle development, glycogen depletion, high pH, reduce tenderness, and shortening shelf life (Botía *et al*., 2023).

Management practices like optimum feeding of quality di*et al*ong with sufficient rest after transportation would improve the carcass pH, yield, color, and fat cover. Meat darkness is high from the meat export market and high-ended domestic (HED) hotels in Ethiopia. However, few authors like Addis *et al.,* 2019 reported about 30.77% DFD meat (14.29% for Harar; 35.71% for Boran; and 45.45% for Arsi cattle breeds). Gadisa, 2018 reported about 38.57% DFD; 22.86% PSE in the wet season and 10.42% DFD; 33.33% PSE in the dry season for Arsi, Bale, and Harar cattle breeds.

Dark meat is often sold at a discounted price and is generally unsuitable for export markets. Even in a developed country, DC meat causes a significant economic loss to the meat industries because consumers reject it at the point of purchase (Warner, 2017). Several pre-slaughter stress factors behind DC meat have been reported in Africa and Ethiopia (Addis *et al*., 2019; Guru *et al*., 2013). Therefore, this review examines the factors behind DC meat in Ethiopia and provides baseline information for the fate of the meat industry in Ethiopia.

3.2.2. Inadequate marbling

Meat characterized by a high marbling value is typically anticipated to have good shear force values, sensory quality, and water-holding capacity (Erena *et al*., 2024; Nogalski *et al*., 2019). The causes of inadequate marbling include genetic factors, breed characteristics, age and nutritional management and feed (Nguyen *et al*., 2021). Most cattle used for beef production in Ethiopia are aged and used after being released from ploughing, which is poor body condition and low product quality (Getachew, 2024). Hence, the proportion of carcasses with little /no fat cover was very high (Mummed, 2015; Mummed and Webb, 2014) . This affects sensory quality and acceptance of the meat (Nogalski *et al*., 2019), limiting Ethiopian meat from the international market.

3.2.3. Capacity to attain export market weight at an early age

Ethiopia has the lowest of beef production per animal. The average carcass weight for indigenous cattle was 136 ± 0.69 kg, which was lower than the African average of 146 kg (Mummed, 2015). According to (Erge *et al*., 2022), fattening different cattle breeds in Ethiopia for ninety days resulted in an average body weight of 216 ±12.21 kg at age of 2 to 2.5 years. Similarly, (Weldegebrial *et al*., 2018) reported a slaughter body weight of 179 ± 01 kg for different breeds after feeding for ninety days at the age of 2 to 2.5 years. However, the export market needed up to 300 kg of live weight at the age of below 2 years for cattle and 25 kg for yearling sheep and goats (Yami *et al*., 2018). The production system from birth to entering the fattening is a practice being undertaken by smallholders (Guru *et al*., 2013). Since the production, feeding, and handling system from birth to entry into feedlots was loaded with chronic stress (Yami *et al*., 2018). Ethiopian cattle and sheep need a long time to attain the required 300 and 25 kg, respectively. Different authors have conducted on-station experiments on the potential and time required to attain the export market standard in Ethiopia. Example (Ashebir *et al*., 2019) reported that Kereyu indigenous cattle breed at age of 1- 1.5 years was attained 292 kg at 179 days, Borana cattle at the age of 1-1.5 years was attained 300.22 kg at 224 days (Guru *et al*., 2013) , yearling Arsi bulls at age of 1 to 1.5 years was attained 240 kg at 238 days (Aman *et al*., 2019), and Afar breed at age of 2 to 2.5 years was attained 300 kg at 254 days (Weldegebrial *et al*., 2018). The long fattening period affects the return rate of producers**.**

3.2.4. Bruising

Bruising occurs due to physical trauma during handling and transportation, resulting in discolored and damaged meat areas (Stella and Piaggio, 2015). In Ethiopia, rough handling during loading and unloading, overcrowded and poorly designed transportation facilities, and the use of inappropriate tools and methods during handling are common causes of bruising (Addis *et al*., 2019). Fighting in lairage and biting during transport to market and abattoirs are also causes of bruising in Ethiopia (Gadisa, 2018; Mummed, 2015). This defect leads to economic losses due to trimming, discarding bruised meat, reduced meat quality, and consumer acceptability (Mummed, 2015). According to (Addis *et al*., 2019) report about 33.33% of bruising was reported from total of 39 samples observed.

3.2.5. Contamination

Microbial contamination of meat is a critical concern in Ethiopia due to poor hygienic practices during slaughter and processing. The main causes include unhygienic slaughterhouse conditions, inadequate sanitation and disinfection practices, and poor handling and storage practices post-slaughter. The impact of contamination includes an increased risk of foodborne diseases, shortened shelf life of meat products, and economic losses due to spoiled meat (Birhanu *et al*., 2017; Tadesse and Gebremedhin, 2015). According to Mummed (2015) between July 2010 to June 2013, Ethiopia lost about 771,666.9 ETB (38,953.4 USD) due to carcass and organ condemnation. Similarly, (Atlabachew and Mamo, 2021) collected samples from Debre Berhan town and

(Teshome *et al*., 2020) from Kara, Burayu, and Dukem towns reported that all samples collected from butcher shops detected a significant count of spoilage microbes. Hence, adequate sanitary measures should be taken from production to consumption stages in the Ethiopian meat industry.

5.2.6. Lack of tenderness

Tenderness is a key quality attribute of meat, and in Ethiopia, it is often negatively affected by genetic factors, diets, the age of the animal at slaughter, and inadequate aging or conditioning of the meat post-slaughter. Tough meat is less desirable to consumers, resulting in reduced consumer satisfaction and marketability, and economic losses due to lower demand for tougher meat (Addis *et al*., 2019; Mummed, 2015). Ethiopian beef cattle are brought to market after being culled from production and in poor body condition (Gadisa, 2018; Mummed, 2015). Increased age and poor body condition at slaughter have resulted in tougher and darker meat (Addis *et al*., 2019). A few reports on instrumental tenderness values for different Ethiopian cattle breeds are indicated low tenderness. According to Timketa *et al*. (2021) report about 30– 56 N for Arsi, 16 - 25 N for Borana, and 15– 25 N for Harar ages of three to seven years old animals were analyzed after the samples were aged for 14 days. Addis *et al*. (2019) reported for similar breeds 42 ± 1.51 N, 21 ± 1.33 N, and 19 ± 1.33 from Arsi, Borana, and Harar cattle, respectively. Similarly, Gadisa *et al*. (2019) reported instrumental tenderness of about 25± 1.42 N for Harar, 41 ± 2.68 N for Arsi, and 41 ± 2.92 N for Bale cattle breeds in Ethiopia.

3.2.7. Presence of parasites

Parasitic diseases like fasciolosis, hydatidosis, and corynebacterium bovis were the major causes of poor animal condition, loss of body weight, carcass condemnation, organ condemnation, and financial loss in Ethiopia (Haben and Isayas, 2024 Teshome *et al*., 2023; Jemal and Kebede, 2016). For instance, inadequate veterinary care, parasite control, poor hygiene, and sanitary conditions on farms and during slaughter, contribute to this problem. The impact includes health risks to consumers and economic losses due to condemned or downgraded carcasses' quality (Haben and Isayas, 2024). According to (Jemal and Kebede, 2016) who reported that only between 2010 and 2011 different parasite causes for financial loss due to organ condemnation in Awasa abattoir was calculated to be 651,342.5 ETB (20,592.03 USD) per annum.

3.3. Major causes of meat quality defects in Ethiopia

3.3.1. Production system

In Ethiopia, livestock are raised in three different production systems: mixed crop-livestock, pastoral and agro-pastoral, and intensive production systems. The environmental conditions, feed quality, and quantity that animals receive differ among production systems. The difference in nutritive value of feeds may in turn have impacts on carcass weight, fatness, muscle glycogen content, and the quality of the meat.

Different scholars Guru *et al*. (2013) ; Weldegebrial *et al*. (2018); Brasesco *et al*. (2019) in Ethiopia reported that carcasses of animals from highland areas are quickly darkened and had a short shelf-life. In contrast Ashebir *et al*. (2019) reported the case of meat darkness is not related to the origin of animals rather than other pre-slaughter handling and genotypes. Below, meat quality effects associated with the different livestock production systems in Ethiopia are discussed.

3.3.1.1 Mixed crop-livestock production system

The mixed crop-livestock production system in Ethiopia is practiced traditionally (Anteneh, 2010), in areas where there is sufficient rainfall (1,503 mm) and moderate temperature (15.6°C) (Moges and Bhat, 2021). Most livestock products that are used for domestic consumption are obtained from the mixed crop-livestock production systems. However, farmers do not sell their products based on demand in a market. About 75% of farmers in this system sell cows after being culled from dairy services (Mummed, 2015). Oxen are sold after the ploughing season. Most of the animals are in poor body condition due to chronic stress and hard work such as draught on the farm. The poor body condition results in low carcass yield, chemical and sensory quality (Anteneh, 2010), and these are ideal conditions for the formation of DC meat due to the higher level of physical activity leading to low muscle glycogen reserves at slaughter.

Hararghe's finishing system, a type of mixed crop-livestock production system, is an exception. In Hararghe, ruminants are finished via a long traditional practice (Abebe and Urge, 2014). The system is largely based on cut-and-carry green feeds from maize and sorghum origin, including thinning, leaf strip of maize, and sorghum plants (Yami *et al*., 2018; Teklebrhan and Urge, 2014). Farmers usually buy young steers from the adjacent lowlands pastoral areas and use them for ploughing and other farm work. In this system, bulls are tethered under shade, finished, and sold before they become old (less than 4 years) and emaciated. The Hararghe bull finishing system is unique in Ethiopia (Tefera *et al*., 2019; Tsigereda & Mengistu, 2011;) reported that Hararghe farmers utilized Fenugreek (*Trigonella foenumgraecum*) flour, fermented dough or their blend, and yeast (*Saccharomyces cerevisiae*) for fattening. This model of finishing cattle minimizes incidences of DC meat. There is no need for long-distance travel to find feed and water. Animals are not heat-stressed since they are tethered under the shade. Animals are also young when they are offered to the market. However, Hararghe's cattle finishing system is only practiced in the Hararghe area and transported long distances of about 350-500 km which causes stress subsequently affecting meat quality at slaughter.

3.3.1.2 Pastoral and agro-pastoral livestock production system

Pastoral and agro-pastoral production systems in Ethiopia are mainly found in the lowlands and largely rely on natural or semi-natural vegetation. Production is subsistence-oriented, and milk is the main product. In Ethiopia, commercial feedlot

operators purchase 3–6-year-old Boran, Kerayu, and Ogaden cattle from the lowlands. Pastoralists and agro-pastoralists sell excess young bulls to highlanders and feedlot operators (FAO, 2019). The young bulls are preferred because they show a good production response to fattening, deliver high-quality beef, and qualify for the standards required by the export market niche for Ethiopian cattle breeds (Ayenew, 2012; Abebe *et al*.,2010). The Boran cattle breed, categorized as *Bos indicus* (humped Large East African Shorthorn Zebu type) is one of the local cattle breeds from the Borana rangelands in southern Ethiopia reared by the Borana pastoralists of Oromo people.

The majority of Ethiopia's livestock supplied for export originate from the pastoral and agro-pastoral areas of Afar, Somali, and Borena. Producers that rear livestock are often located in rural areas where access to markets and infrastructure is insufficient. Hence non-specialized trucks and improper handling transportation are used to bring animals to the market, which causes stress (Gadisa, 2018; Mummed, 2015). Prolonged nutritional restriction and overstocking which may happen in agro-pastoral and pastoral systems in Ethiopia are stressful. Chronic stress may also happen in overstocking due to heavy parasite burdens (Gizaw *et al*., 2021). The other problem in the pastoral and agro-pastoral livestock production system is seasonal feed fluctuation and associated feed scarcity. The animals are forced to travel long distances in search of feed and water in warm climate conditions which causes chronic stress. All these stress conditions may lead to the depletion of stored glycogen before slaughter which in turn may result in DC meat (Adzitey and Nurul, 2011).

3.3.1.3. Intensive livestock production system

The intensive livestock production system is practiced in urban and peri-urban areas of Ethiopia (USAID, 2016). Finishing animals under an intensive system offers an opportunity for livestock producers to sell their products in the domestic market as well as to export (Ayenew, 2012). However, season-dependent feed availability affects the quality of animals delivered to the market (Genet *et al*.,2017; Teklebrhan and Urge, 2013). In commercial feedlots, a large number of unfamiliar animals, about 1000-1500 heads of cattle, are fed in one barn (Teklebrhan and Urge, 2013). Usually, there are no individual pens in Ethiopian feedlot farms. The intensively-finished animals are less prone to develop DC carcasses than extensively-finished cattle as natural pasture has lower energy than concentrates (Hughes *et al*., 2014).

The reports given by; (Yami *et al*., 2018; Legese and Fadiga, 2014; Abebe *et al*., 2010) stated that goat and sheep carcasses from highland areas of Ethiopia quickly darkened and had a short shelf-life compared with those from lowland areas. In contrast, Merera *et al*. (2013) reported that the darkening of mutton from both highlands and lowlands was not different. Meat darkness is mostly the result of feeding energy-rich diets before slaughter to restore glycogen depletion. This perception are supported by Legese and Fadiga (2014) who reported that exporting highlands sheep is underway to Bahrain since the country has developed a taste for Ethiopian highlands sheep meat.

It is, therefore, important to investigate if the meat darkness difference between highland and lowland small ruminants is due to environment, genetics, or their interaction.

3.3.2. Diet

In Ethiopia, crop residues of cereals and pulses account for about 32% of the total feed utilized and these are ranked second to grazing, which constitutes 37% (CSA, 2022). However, both feed resources are only available seasonally and are low in quality. Crop residues of cereals contain crude protein (CP) levels below 8% and neutral detergent fiber (NDF) of above 55% with limited intake and lower digestibility (Bediye and Sileshi, 1995). Steers raised on pasture had a significantly lower glycolytic potential and the pH/temperature decline rate of carcasses was slower than those from feedlot systems (Webb and Erasmus, 2013). Thus, feeding high-energy diets or energy supplements during the finishing period of cattle and sheep may be useful to reduce the occurrence of meat quality defects (Ponnampalam *et al*., 2017). A finishing diet can improve meat quality, especially appearance and aroma, as well as the fat level and color. Feeding supplements in the last 7 days before slaughter has been reported to reduce the relative risk of DC meat by 25% (Loudon *et al*., 2019). Moreover, provision of rest for two weeks at or near the abattoir before slaughter are beneficial for minimizing meat defects (Walsh *et al*., 2019).

3.3.3. Breeds or genotype

There is variation in meat quality among species and animals within a species. Variation among animals reared in the same environment and slaughtered at the same age, weight, and degree of finish suggests a genetic cause (Yami *et al*., 2018). Genetic variation can influence the biochemical and structural characteristics of muscle fibers and intramuscular connective tissue when selection is used to achieve production efficiency and improve meat/flesh quality (Listrat *et al*., 2016). Dairy breeds are characterized by higher levels of myoglobin and thus iron in their muscle (Dunne *et al*., 2004), which can affect the color of meat.

In Ethiopia, there is no specific cattle breed that is exclusively selected for beef production, nor has there been development of indigenous breeds for production traits (Assefa, 2017). However, a recent report indicated that the Borana cattle breed is targeted for enhanced contribution to the beef industry in Ethiopia (ATO, 2020) as it is already for some African countries like Botswana, Namibia, and South Africa (Yami *et al*., 2018). According to Legese and Fadiga (2014) standard live weight of animals to be exported alive for a bull is 300- 320 kg, and for sheep and goats is 14-27 kg. Ethiopian sheep and goats have low average carcass weights. This might be due to poor genetic performance, poor animal husbandry practices, or their combination (Legese and Fadiga, 2014). In general, comparative research on breed characterization for meat production potential and other production traits for various livestock species in Ethiopia is limited (Worku *et al*., 2020), and warrants further investigation.

3.3.4. Livestock management

Feed additives and hormonal additives, such as the application of metabolic modifiers, growth promoters, and hormone implants, have both positive and negative effects on meat quality, depending on the type, dose, and objective of use. The positive impacts are enhanced yield and appearance, whereas negative effects are reduced marbling, tenderness, and flavor in meat and public health problems. Different countries have different policies on the use of additive feed inclusion. For example, the European Union banned hormonal implants in 1988, Australia panelised the beef from cattle treated with growth-promoting, and in contrast, America uses it in specific farms.

In Ethiopia, not all livestock species have access to housing. According to the report of (Gadisa, 2018), only about 10% of livestock producers provide housing or shade for their animals. The housing of large animals after weaning is rare in Ethiopia, as the housing is prepared from locally available material for calves, small ruminants, and poultry, mostly to protect them from predators. Even in most feedlots, animal houses are exposed to sun, rain, and wind without overhead cover, because the shade is only provided to sick animals (Teklebrhan and Urge, 2013). Exposing animals to extremely high and low temperatures (fluctuations in weather conditions) is a cause of animal stress which resulting in a depletion of muscle glycogen storage before slaughter and lead to high pH meat (Ponnampalam *et al*., 2017). Therefore, uses of houses based on agro ecologies prevent animals from climate burdens and enhance meat quality.

Stocking density at the feedlot, free grazing, and inadequate shelter housing contribute to animal pre-slaughter stress. Commercial feedlots keep large groups of unfamiliar animals (1000-1500 heads of cattle) in one barn because there is no compartment house/barn with a specific dimension for both feeding and watering troughs (Teklebrhan and Urge, 2013).

3.3.5. Age of animal at slaughter

The age at slaughter significantly affects meat color (Ponnampalam *et al*., 2017). Age at slaughter is determined by many factors such as production system, nutrition, and growth rate, all of which have positive relationships with the darkness of meat (Gadisa *et al*. 2019; Ponnampalam *et al*., 2017). An older animal has darker meat due to higher muscle pigment (myoglobin) content and/or lower muscle glycogen concentration and fiber size increases with animal age in all species (Listrat *et al*., 2016). In Ethiopia, there is potential for indigenous cattle breeds to produce beef of sufficient quality to satisfy both domestic and export demand if appropriate breeding strategies are designed and supported by proper management (farm to abattoir) and feeding strategy. Dairy-beef as a resource is also underutilized in Ethiopia (Mummed, 2015) reported that cattle less than two years of age were not slaughtered in Ethiopian abattoirs. A young animal is demanded by export markets because it is a good source of lean and tender meat. Bull calves at an intensive dairy farm in Ethiopia are early (three days to a month) culled to minimize the cost incurred by the farm (Gadisa, 2018). Hence, producers sell calves

at an early age. However, marketing dairy calves for meat is not common (Mummed and Webb, 2014). Therefore, these young bulls are given to relatives in the rural areas and unfortunately, are unlikely to survive due to inappropriate feed, health, and housing.

3.3.6. Transportation

Most animals are transported at least once in their lifespan from farms to auction centers (Chulayo *et al*., 2012). Since there are no specially built trucks for animal transport in Ethiopia, livestock is often transported via walking from farm to market. The absence of dedicated animal transport contributes to quality deterioration as a result of injury and stress (Yami *et al*., 2018). Moreover, pre-slaughter stress due to inappropriate handling and transportation causes carcass damage through bruising, dark firm dryness, and reduction in live weight (Addis *et al*., 2019). Bruising and lesions downgrade carcasses, and meat quality problems such as dark, firm, and dry (DFD) meat can be detected (Jerlström, 2013). Bulitta *et al*. (2012) reported that about 16% of animals die and 10.7% of animals are injured during transport from Gudar to Finfine. This journey forces animals to walk long distances (250-300 km) across wide rivers that have no bridges without sufficient feed, water, and rest. Long-distance traveling increases the levels of intramuscular creatine kinase and lactate dehydrogenase enzymes that indicate physiological responses to stress during transportation (Alam *et al*., 2018). Release of these enzymes adversely affects meat quality due to rapid glycolysis and increased lactate production, which increases ultimate pH (Chulayo *et al*., 2012). Vehicular transport often entails deprivation of feed and water for long periods, rough handling before and during transport, exposing animals to temperature extremes or severe weather, and vibration of the truck, all of which contribute to the stress (Addis *et al*., 2019; Bulitta *et al*., 2012). In particular, sheep and goats have a high mortality rate and rapid loss of live weight during long-distance ground transportation (Teklebrhan and Urge, 2013). Air transport is less stressful and shows a lower mortality rate as compared to foot, trucking, and sea transportation. However, the cost of air transportation is a major challenge as it is not affordable for smaller operations (Legese & Fadiga, 2014).

3.2.7. Lairage

Lairage is used as a collection place for animals just before slaughter. This place is designed to provide animals with a recovery period from transport stress (Merten *et al*., 2011). Mummed (2015) reported bruising, contamination, pneumonia, and poor bleeding are the major causes of meat defects in Ethiopia. This bruising has occurred due to excessive use of sticks during transport and lairage, as well as due to an absence of clean, dry bedding and enough space in lairage (Addis *et al*., 2019). Also, in lairage, drinking water and feed must be available, with lack of water sometimes dehydrating animals before slaughter (Birmaduma *et al*., 2019; Mummed, 2015). In Ethiopia, most of the abattoirs lack lairage, thus animals fight, and injury occurs, and there is no opportunity for sufficient rest at the slaughterhouse before slaughter. Such additional

physical demands experienced by animals before slaughter may lead to fatigue, negatively impacting meat quality.

Diseases

Disease is a state in which normal physiological functions are disturbed or altered at the cellular, tissue, organ, or whole organism level. Ethiopia is endemic to some livestock diseases (Gizaw *et al*., 2021). These endemic diseases are a major obstacle to the development of the livestock industry as they adversely affect livestock production and exports. For example, foot and mouth disease outbreaks appear every year in almost any corner of the country (Wubshet *et al*., 2019), that led to millions of USD losses due to the restriction or rejection of livestock products in the international market (Zewdie *et al*., 2023). Mostly, an outbreak occurs at a particular time while change in the natural 'balance' between the host, agent, and environment appears (FAO, 2018). These might be due to exposure to pathogenic micro-organisms, poor management especially related to feeding, stress, poor genetic selection, and toxic agents. Exhaustion and exposure of animals to dust during long-distance trekking to search for feed and water in route to markets and abattoirs, lack of shelter, and overcrowding are causes of chronic stress and is a conducive environment to disease (Mummed, 2015). These diseases cause huge economic losses to producers and livestock exporters (Gizaw *et al*., 2021) . Using veterinary vaccines to control animal diseases is an effective strategy in Ethiopia. However, control of FMD by vaccination is difficult due to genetic variation between the serotypes (Woldemariyam *et al*., 2023), multiple sources of infection, such as production system, geographic location, age of animals, contact with wildlife, season of the year, mixed animal species (Zewdie *et al*., 2023) and indirect like disease knowledge, high vaccine costs, limited vaccine availability, and administration difficulties (Bekele *et al*., 2018).

Government efforts and policy have moved away from disease issues leading to different trade bans. Trans-boundary animal diseases (TADs) such as CBPP (Contagious Bovine Pleuropneumonia), CCPP (Contagious Caprine Pleuropneumonia), FMD (Foot and Mouth Disease), LSD (Lumpy Skin Disease), AHS (Africa House sickness), PPR (Pest des Petits Ruminants) and NCD (New castle Disease) are limiting the productivity, market access of livestock and their products to regional and international markets (Seyoum and Teshome, 2018).

3.2.8. Market infrastructure

Market infrastructure components for meat export in Ethiopia are underdeveloped. Transporting live animals and meat from the abattoir using a non-specialized truck affects the shelf-life of meat (Arse Gebeyehu, 2013). In Ethiopia, most abattoirs do not have sufficient chilling and freezing facilities (EDMID, 2016). The packing system of most meat exporter abattoirs in Ethiopia currently uses very poor technology. Ethiopian customers, including Middle Eastern and Angolan importers, often complain about the carelessness and poor quality of meat packaging supplied by Ethiopians.

Covering with the stockinette is the only packing technology currently used by most exporters (EDMID, 2016).

Another important issue is the lack of a specific brand name for Ethiopian meat and live animals. The absence of branding is the cause of the country's economic loss as a whole due to the rejection of exported products (Frimpong, 2009). Almost all meat-exporting countries like New Zealand, Australia, and Brazil have their brand in the international market. Some reasons for the bad image of Ethiopian meat products are poor quality, lack of global recognition and limited promotion, unresponsive to business communications, and unreliability in meeting contractual obligations (EDMID, 2016).

In general, poor animal handling results in the loss of weight, physical injuries, sickness, reduced meat color, and even death from poor welfare conditions. Hence, as Ethiopia struggles to address its meat quality issues, there is a need for a strong and consistent strategy concerning live animal management/pre-slaughter animal handling and post-slaughter processing in addition to improving infrastructure (markets, slaughterhouses, farm installations) and training farmers and stock persons in general handling of animals and good practices to satisfy domestic and international markets.

3.3. Strategies to minimize meat defects in Ethiopia

Prior to slaughter, livestock must be monitored during feeding, implanting, penning, processing, transporting, and holding (Chulayo and Muchenje, 2017). If proper steps are taken to reduce stress and allow for acclimation and rest following a stress event, the incidence of carcass defects will be greatly reduced. Nonetheless, identifying animals at a higher risk of stress and preventing stress from occurring remains a challenge for the industry. To minimize meat defects in the Ethiopian meat sector, the development and implementation of the following options are important:

Production: Reorient livestock production system to produce quality products that meet the domestic and export market demands. Producers should consider breed, market demand, and the livestock management practices in the plan of production (Yami *et al*., 2018). There is a need to stimulate private sector investments to modernize and improve the sector competitiveness by promoting the commitment of commercial fattening and finishing to create models that will enhance yields and quality (Brasesco *et al*., 2019; Yami *et al*., 2018).

Nutrition: From a nutritional standpoint, providing a high-energy diet, particularly during the finishing phase and before marketing increases intramuscular glycogen concentration (Merera *et al*., 2013), improves the growth rate, reduces slaughter age, and increases meat tenderness. For two to three weeks before slaughter, supplement a good energy source diet to replace/restore muscle glycogen depleted during travel to the abattoir (Merera *et al*., 2013).

Breed: First and foremost, it is crucial to develop stress-resistant breeds (Knap and Wilson, 2020). Many authors have discovered a high incidence of DC in stress-prone animals (Ponnampalam *et al*., 2017). This is because animals' responses to stress are governed by a complex interaction of genetic factors and prior experiences. Nonetheless, tropical breeds are resistant to stress but grow slowly. Temperate breeds, on the other hand, are more vulnerable to stress but grow at a faster rate. A mix of genotypes from temperate and tropical regions could help reduce the prevalence of DFD meats (Adzitey and Nurul, 2011).

Controlling diseases: Disease outbreaks disrupt the proper livestock husbandry system (Heath, 2012). Even clinical and subclinical livestock disease conditions reduce the efficiency of livestock production, which negatively affect food and nutritional supply and income (Eshetie and Kelifa 2018). There is no disease-free zone in Ethiopia. Hence, cattle illness, infection, and diseases are critical causes of stress (Management Entity, 2021) that damage muscle enzymes which are strongly associated with lower meat quality (Loudon *et al*., 2019). Animal health interventions tend to focus on transboundary or zoonotic animal diseases and little attention is given to diseases in smallholder farmers settings (Alemu *et al*., 2019). However, the main sources of export animals are smallholder farmer mainly in pastoral areas of Ethiopia (Yami *et al*., 2018). Thus, the government should try to establish holistic and robust animal health information system; strengthen the quarantine, inspection, and certification system; improve animal welfare by raising public awareness and introducing good practices; improve the implementation capacities of Ethiopian's animal health services through preparation, endorsement, and implementation of various legal frameworks; and build an advanced animal health system by restructuring veterinary services in line with World Organization for Animal Health (Brasesco *et al*., 2019). However, different diseases need different strategies to control the outbreak. For example, FMD is very economical and causes to rejection of meat from the export market. Hence, different authors developed different strategies to control FMD (Mashinagu *et al*., 2024; Zewdie *et al*., 2023).

Marketing: The livestock supply base to the export and the HED markets is narrow and largely limited to animals of lowland origin due to special tastes and preferences (flavour, meat color, etc.) developed for lowland animals (Yami *et al*., 2018). Land allocated for livestock auction centers is small, hence none can accommodate the separation of animal types. Therefore, whilst livestock marketing is held is less equipped overcrowding, novelty, and lack of sanitation are major causes of stress due to almost no auction center facilities are available(Mummed, 2015; Gadisa, 2018) . Established feed and water at auction places are necessary, and the development of a price policy through premium payment for the young and well-finished animals for meat purposes will incentivize producers.

Transportation: Animals are transported to markets for sale or directly from farms to abattoirs. In either case, stress should be kept to a minimum. Keep transportation and marketing times to a minimum. Vehicles used to transport animals must provide

adequate ventilation, be well-maintained, and driven smoothly. Animals should be provided with access to shade, water, and food, especially if they will remain in the market for an extended period. Keep animals together in their rearing group because mixing unfamiliar animals will result in fighting (Mummed and Webb, 2015). Overcrowding should be avoided as it increases the occurrence of DC meat because of stress.

Slaughtering Process**:** Before slaughter, animals should be rested at the abattoir to allow for sufficient recovery from the stress of travel or transport (Chulayo and Muchenje, 2017). Lairage time should also be kept to a minimum. If the animals will be spending more time in the lairage, there is a need to provide them with food and water. If the animals will be kept in lairage for a longer time than expected place bedding on the floor and feed energy concentrates to replenish muscle glycogen. Mist water can be sprayed on animals to keep them cool, especially when the weather is hot. Abattoirs must be well-designed to ensure that the animals are subjected to as little stress as possible prior to slaughter (Birmaduma *et al*., 2019; Mummed, 2015;). Mechanical stunning (captive bolt pistol, percussion stunner, or free bullet), electrical stunning, and anesthetic gas (CO_2) all render animals' unconscious prior to sticking rather than using hammers and knife which are currently used in most municipal abattoirs. If done correctly, this has the potential to reduce pain, distress, and struggling after sticking and, as a result, can help reduce the incidence of DC meat. To reduce distress, animals must be well restrained before stunning and/or sticking (Anika *et al*., 2024). Promoting the uptake of food standards by slaughterhouses via accessing facilities, the use of modern instruments, and periodic training and health treatment for abattoir workers will also likely contribute to improved meat quality (Muleta, 2022).

Post-slaughter: After dressing, the carcasses should be chilled. Different cooling rates can influence the rate of pH drop via hydrogen ion production as well as the onset of rigor mortis. This has the potential to harm the carcass and meat quality (Ponnampalam *et al*., 2017). The modern chilling practice focuses on speeding up the chilling process by using refrigerated air to reduce microbial growth and evaporative weight loss. The carcass classification system should be demonstrated at all levels. An all-inclusive approach focusing on improving sanitary conditions and strengthening routine meat inspection procedures and reporting systems should be improved and applied (Haben and Isayas, 2024).

Appropriate strategies**:** Developing a consistent strategy to improve technical and economic results of primary meat production, carcass quality, commercial cuts, and meat products made from fresh meat should be in place to drastically reduce issues related to meat quality defects. To benefit meat suppliers and meet demand of the consumers, government policy should consider developing a price policy and implement quality-based payment for meat and live animals (Yami *et al*., 2018; Mummed and Webb, 2015;). It should also include the development of adequate animal health services and the establishment of an internationally accredited

certification system for meat exports, as well as efficient and transparent livestock marketing systems (Mummed, 2023). A strong animal welfare policy, market promotion, and continuous monitoring also should be developed (Mummed and Webb, 2015).

4. Conclusion and Recommendations

Ethiopian livestock production value chain is long and fully challenged with diverse factors that causes chronic stresses. These chronic stresses are fundamental causes for low-quality meat. Hence in Ethiopia, low-quality meat is the major challenge inhibiting meat consumption at high-end domestic hotels and export markets. This review indicated that low-quality meat arises from production practices, disease burden, handling practices, and poor-quality feeds supplied to indigenous livestock breeds. Therefore, reorienting livestock production is critically important in Ethiopia to respond to the meat quality requirements of high-end domestic and export markets. Government policy changes are important concerning on establishing animal disease free zone, animal welfare like animal handling, production, and slaughter if Ethiopia is to become able to supply sufficient acceptable products domestically and to the export market.

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Strengthening Agricultural Supply Chains and Market Systems in Ethiopia: A Critical Systematic Review of Innovative Interventions, Practical Lessons, and Scalable Strategies for Transformational Impact

Sileshi Tamene Fikadu

Department of Geography and Environmental Studies, Wollega University, Gimbi, Ethiopia.
Corresponding Author: sileshitamene@gmail.com

Abstract

Ethiopia's agricultural sector, which supports the livelihoods of millions of smallholder farmers, continues to face persistent structural challenges in supply chains and market systems. Weak linkages, inadequate infrastructure, limited market access, and weak institutional coordination constrain productivity, inclusiveness and value addition. This study critically examines innovative interventions and practical experiences aimed at strengthening agricultural supply chains and market systems in Ethiopia to inform scalable strategies for transformational impact. Adopting a critical systematic review design, the study applied thematic synthesis and cross-case comparison methods to analyze evidence drawn from 50 peer-reviewed articles, grey literature, program evaluations and policy documents published between 2000 and 2024. The analysis focused on six thematic areas: aggregation systems, digital platforms, infrastructure, agro-processing, financial access, and policy frameworks. Successful interventions such as digital market information platforms, farmer aggregation centers, and cooperative-led agro-processing initiatives emerged as effective models that improved market efficiency, reduced post-harvest losses, and enhanced smallholder inclusion. However, challenges related to scalability, coordination gaps, and regional disparities remain significant. To accelerate agricultural transformation, scaling up context-specific best practices, strengthening public private partnerships, enhancing rural infrastructure, and ensuring policy coherence are detrimental. Institutional capacity building and inclusive market governance are essential to ensure sustainability and impact at scale.

Keywords: Aggregation, governance, Interventions, policy frameworks

1. Introduction

Agriculture remains the cornerstone of Ethiopia's economy, employing about 70% of the population and contributing significantly to GDP and exports (Gebremariam *et al.*, 2024; Mekonnen *et al.*, 2024). Despite its central role, the sector continues to face persistent structural challenges fragmented market linkages, limited access to finance and infrastructure, weak institutional coordination, and inadequate storage and transport systems that undermine productivity and sustainability (Abate *et al.*, 2023; Shikur, 2023). These constraints restrict smallholder farmers participation, value addition, and the broader goal of agricultural transformation.

Over the past two decades, numerous studies and programs have promoted market-oriented reforms, digital innovations, and public–private partnerships to address these bottlenecks (Boru *et al.*, 2024; Devaux *et al.*, 2018). Initiatives such as the Ethiopian Commodity Exchange (ECX), agro-processing industrial parks, and rural infrastructure investments have enhanced transparency and market access, while mobile-based platforms have improved information flow through scalability and inclusiveness remain limited (Dhulipala *et al.*, 2024; Gashaw & Kibret, 2018).

Despite these efforts, significant gaps persist in systematically evaluating the effectiveness and scalability of such interventions. Much of the existing literature highlights localized successes but fails to address broader institutional and structural limitations (Gebreyes *et al.*, 2021; Kang'ethe *et al.*, 2021). Moreover, few syntheses integrate cross-sectoral experiences linking digital transformation, cooperative models, and coherent policy frameworks (Endris *et al.*, 2024; Visser *et al.*, 2012).

Emerging scholarship emphasizes multi-stakeholder innovation systems and inclusive governance models to foster adaptability and shared learning across actors' government, private sector, NGOs, and farmer organizations (Lema *et al.*, 2024; Lemma *et al.*, 2008). However, these models often struggle with coordination failures, power asymmetries, and inconsistent policies, particularly in decentralized contexts (Gebremariam *et al.*, 2024; Davis *et al.*, 2019).

To address these challenges, this critical systematic review synthesizes literature published between 2000 and 2024 to evaluate the effectiveness of innovative interventions in strengthening Ethiopia's agricultural supply chains and market systems. Focusing on six thematic pillars aggregation systems, digital platforms, infrastructure, agro-processing, financial access, and policy frameworks the study identifies practical lessons, scalable strategies, and key enablers for transformational agricultural change in Ethiopia.

Despite the central role of agriculture in Ethiopia's economy, persistent structural bottlenecks such as fragmented value chains, limited market access, and underdeveloped infrastructure have stifled inclusive growth and sustainable transformation (Gebremariam *et al.*, 2024; Mekonnen *et al.*, 2024). While numerous initiatives have been implemented by development actors and institutions over the past two decades, there remains a fragmented understanding of what works, under what conditions, and why.

A critical systematic review offers a robust, evidence informed approach to synthesize dispersed findings, evaluate the effectiveness of interventions (measured through indicators such as productivity gains, cost efficiency, post-harvest loss reduction, and market access improvement), and assess scalability based on replication potential, institutional adoption, and regional adaptability (Gebreyes *et al.*, 2021; Devaux *et al.*, 2018). This analytical framework helps identify patterns across themes such as

aggregation systems, digital innovations, rural finance, infrastructure, agro-processing, and enabling policy environments.

Beyond descriptive summaries, the study provides a critical interrogation of underlying mechanisms and institutional dynamics (Lema *et al.*, 2024; Kang'ethe *et al.*, 2021). The findings will inform evidence-based policymaking by identifying practical pathways for strengthening coordination between government agencies, the private sector, and cooperatives. The review also supports ongoing efforts to align agricultural transformation agendas with Ethiopia's broader strategies for rural development, poverty reduction, and food system resilience (Boru *et al.*, 2024; Abate *et al.*, 2023). Ultimately, it bridges knowledge gaps while providing a strong empirical foundation for adaptive policy design and implementation.

The systematic review is guided by the following specific, measurable, achievable, relevant, and time-bound (SMART) objectives:

- To systematically identify and categorize innovative interventions implemented between 2000 and 2024 across six key thematic areas aggregation systems, digital platforms, infrastructure, agro-processing, financial access, and policy frameworks targeting agricultural supply chains and market systems in Ethiopia.
- To critically assess the effectiveness of these interventions using performance indicators such as improved market efficiency, reduced post-harvest losses, enhanced farmer income, and strengthened institutional coordination, across varied agro-ecological and socio-economic contexts.
- To evaluate scalability and adaptability by examining the extent to which successful interventions have been replicated, institutionalized, or regionally expanded under different implementation conditions.
- To extract and synthesize practical lessons and enabling factors from successful multi-stakeholder models, particularly those integrating digital tools, cooperative structures, and supportive policy environments.
- To develop evidence-based, scalable strategies and policy recommendations aimed at transforming Ethiopia's agricultural market systems by 2030, with a focus on inclusivity, sustainability, institutional coordination, and regional equity, thereby directly informing national agricultural transformation policy processes.

2. Materials and Methods

The study employed a critical systematic review approach to identify, appraise, and synthesize diverse evidence on innovative interventions and scalable strategies aimed at strengthening agricultural supply chains and market systems in Ethiopia. The methodology was guided by the PRISMA 2020 framework for systematic reviews (Page *et al.*, 2021) and tailored to the context of agricultural transformation in low- and middle-income countries.

2.1. Research design

A critical systematic review design was adopted to enable a rigorous and structured synthesis of both qualitative and quantitative sources. This design allowed for the integration of empirical studies, programmatic reports, and policy documents to ensure methodological rigor and contextual sensitivity. The review combined thematic synthesis and cross-case comparison to identify actionable lessons and scalable best practices (Malterud, 2012; Onwuegbuzie *et al.*, 2012).

2.2. Study selection

The review followed the four-phase PRISMA 2020 process: identification, screening, eligibility, and inclusion (Page *et al*., 2021). After duplicate removal, 158 records were screened by title and abstract; 89 full-text documents were assessed against eligibility criteria. Ultimately, 50 high-quality studies were retained. Two independent reviewers conducted screening, and disagreements were resolved through discussion or consultation with a third reviewer (Ahn & Kang, 2018).

2.3. Data extraction

A structured template captured key data points: author(s), year, intervention type, location, methodology, key outcomes, success factors, and lessons learned. Extraction was conducted iteratively, with pilot testing on five studies to refine the framework (Mohamed Shaffril *et al.*, 2021).

2.4. Quality assessment

The methodological quality of included studies was appraised using an adapted Mixed-Methods Appraisal Tool (MMAT). Each study was scored on four criteria-clarity of design, data validity, analytical transparency, and contextual relevance using a three-tier scale (High = 3, Moderate = 2, Low = 1). Studies scoring below 2 (≤50%) were excluded or flagged for cautious interpretation. For peer-reviewed studies, journal credibility and citation strength were considered. For grey literature, author credibility, data transparency, and institutional reliability were assessed (Malterud, 2012; Onwuegbuzie *et al.*, 2012).

2.5. Data synthesis

The synthesis combined systematic text condensation (Malterud, 2012) and thematic synthesis (Onwuegbuzie *et al.*, 2012) across six thematic domains: Aggregation systems, digital platforms and ICT tools, rural infrastructure and logistics, agro-processing and value addition, financial access mechanisms, policy and institutional frameworks.

The thematic synthesis was operationalized through a three-stage coding process:

- Initial coding of extracted data to identify recurring patterns and concepts.
- Axial coding to cluster related sub-themes and establish cross-case linkages.

- Selective synthesis to develop overarching analytical categories and interpretive models.

Coding was conducted using NVivo 12 Plus software to ensure systematic management of qualitative data. To enhance reliability, two reviewers independently coded a 20% subset of the data, achieving an inter-coder agreement rate of 0.84 (Cohen's Kappa).

Cross-case comparisons were used to triangulate evidence and identify contextual factors influencing success, scalability, and policy relevance. The resulting synthesis informed the development of an integrated model for strengthening Ethiopia's agricultural supply chains.

3. Results and discussion

The result section presents the synthesized findings of the critical systematic review across seven thematic areas, reflecting the scope and diversity of innovative interventions, strengths, gaps, and emerging practices in Ethiopia's agricultural supply chains and market systems. Data were extracted from 50 peer-reviewed and grey literature sources, government reports, and development program evaluations published between 2000 and 2024. Quantitative synthesis was applied where data permitted, with reported success rates and effect sizes summarized for comparability.

3.1. Aggregation and cooperatives

Aggregation models through cooperatives, farmer unions, and producer organizations significantly improved market participation and negotiation capacity. Across 17 evaluated programs, collective marketing increased farm-gate prices by 15–35%**,** while transaction costs fell by 20–25% (Gebreyes *et al.*, 2021; Mekonnen *et al.*, 2019). In Oromia and Amhara, strong unions like Lume Adama and Gozamen Multipurpose Cooperatives achieved consistent profit margins through bulk sales. However, weak governance, limited autonomy, and management inefficiencies constrained long-term viability (Boru *et al.*, 2024; Davis *et al.*, 2019). Externally facilitated cooperatives with bundled services such as access to inputs and finance—showed higher sustainability.

3.2. Digital and ICT-enabled market platforms

Digital tools emerged as transformative enablers of market efficiency, particularly in addressing information asymmetries. Platforms like ATA's 8028 hotline reaching over 5 million users by 2023 and E-LMIS improved market transparency (Abate *et al.*, 2023). Mobile-based platforms reduced information delays by 40% in pilot regions (Dhulipala *et al.*, 2024). However, poor internet connectivity and digital illiteracy limited adoption, especially in Gambella and Afar. Blended interventions such as the AgriHub model achieved higher uptake (65%) farmer participation by linking digital tools with cooperative marketing (Alemu & Koomen, 2023).

3.3. Value addition and agro-processing

Agro-processing interventions yielded measurable productivity and income gains. Integrated Agro-Industrial Parks (IAIPs) in Amhara, Oromia, and SNNPR created over 25,000 jobs and reduced post-harvest losses by 10–18% (Gebremariam *et al.*, 2024). Small-scale value addition initiatives such as women-led honey cooperatives in Sheka and dairy processing units in Jimma boosted household incomes by 30–45% (Mekonnen *et al.*, 2024; Lemma *et al.*, 2008). However, limited infrastructure and market linkages restricted scalability. These successes underscore the importance of coupling processing initiatives with skills training, packaging innovation, and market-led clustering.

3.4. Access to finance

Financial access interventions remain uneven but show promising results where innovative mechanisms are applied. Warehouse receipt systems and mobile-based credit platforms improved liquidity and input access, with repayment rates exceeding 85% among trained users (Lidder *et al.*, 2024). Cooperative-led credit models increased female participation in financial services by 28% (Endris *et al.*, 2024). Yet, high collateral demands, and perceived lending risks persist. In Oromia, blended finance pilots under the ATA Credit Guarantee Scheme catalyzed ETB 1.2 billion in private agribusiness loans, indicating the potential of risk-sharing models.

3.5. Infrastructure development

Infrastructure investment remains uneven across regions. Analysis of 15 infrastructure projects showed that improved feeder roads and storage facilities reduced post-harvest losses by 20–40%**,** particularly in Oromia and Amhara (Tesfaye *et al.*, 2023; Kassaye *et al.*, 2022). However, Afar, Somali, and Gambella regions lagged, with less than 30% of rural markets accessible by all-weather roads (Lema *et al.*, 2024). Integrating physical infrastructure with digital logistics solutions remains a key unmet opportunity.

3.6. Policy frameworks

National and regional policies such as the Agricultural Transformation Agenda and IAIP Strategy provided enabling frameworks for commercialization. Policy-linked programs with strong public–private partnerships achieved clearer market coordination and higher institutional ownership (Kirina *et al.*, 2022). However, implementation gaps persist, especially in translating national frameworks into regionally actionable plans. Multi-stakeholder platforms under the Agricultural Commercial Cluster (ACC) model emerged as effective vehicles for coordination.

3.7. Practical lessons and scalable strategies for transformational impact

Across all themes, quantitative synthesis revealed that integrated, multi-stakeholder models increased supply chain efficiency by 25–30%, with digital integration and cooperative-based aggregation driving the strongest outcomes. Successful interventions were characterized by:

- Strong institutional linkages and blended finance
- Integration of ICT tools in service delivery
- Contextual adaptation and local ownership
- Inclusion of women and youth

Scalability was highest when interventions were co-owned by local institutions and underpinned by policy incentives. Sustained transformation, however, depends on bridging regional disparities and embedding inclusive market governance.

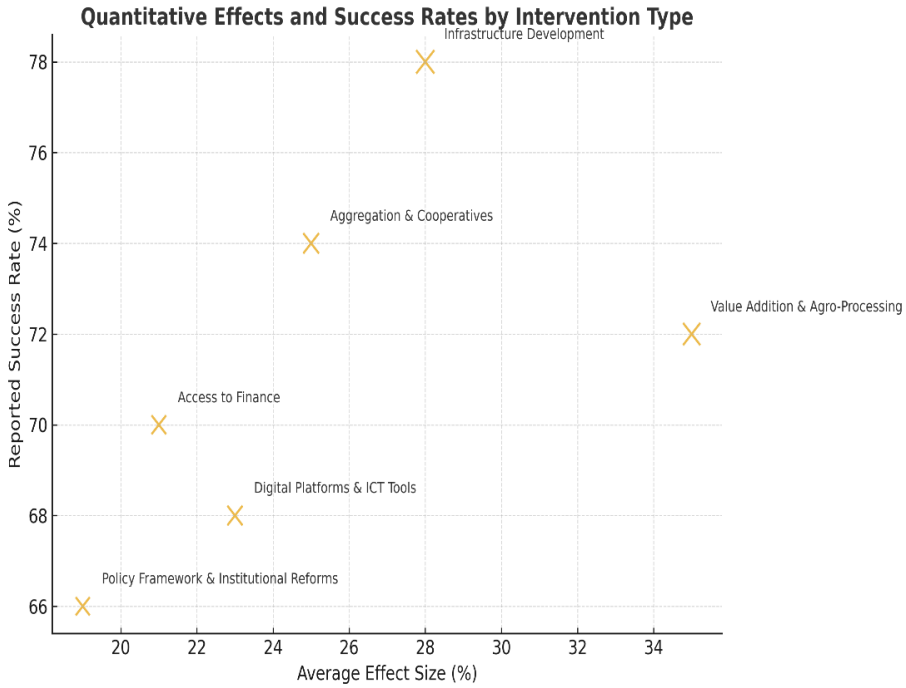

Figure 3: effect magnitudes and success rates across intervention types

From the above figure, the relationship between the average effect size (measured as a percentage improvement in target outcomes) and the reported success rate of key agricultural interventions identified in the systematic review. Interventions related to value addition and agro-processing and infrastructure development showed the highest combined effectiveness and success rates, indicating strong potential for scalability. Policy and institutional reforms, while foundational, demonstrated lower direct effect sizes due to implementation and coordination challenges.

Systematic review aimed to explore innovative interventions, practical lessons, and scalable strategies for strengthening agricultural supply chains and market systems in Ethiopia, synthesizing evidence from 50 sources spanning 2000–2024. The results present a nuanced understanding of the thematic areas, shedding light on the strengths, challenges, and opportunities that characterize the agricultural landscape in Ethiopia.

3.8. Aggregation systems: successes and challenges

Cooperatives and farmer unions have been central to improving smallholder market participation. Successful models integrated capacity-building, input access, and collective marketing services, particularly in Oromia and Amhara (Mekonnen *et al.*, 2019; Lemma *et al.*, 2008). Their ability to enable bulk sales and better price realizations underscores the potential of structured aggregation mechanisms (Boru *et al.*, 2024; Davis *et al.*, 2019).

However, governance issues, lack of autonomy, and limited institutional support have hindered sustainability (Gebreyes *et al.*, 2021). Externally facilitated cooperatives performed better than grassroots-initiated ones, emphasizing the role of institutional backing. Socio-economic barriers, such as uneven resource access and varying literacy levels, also contributed to divergent outcomes. Financial and extension service integration further enhances sustainability (Jembere et al., 2023). These observations suggest that structural context and institutional support are critical determinants of success.

3.9. Digital platforms and ICT tools: Bridging the gap

Digital tools, such as the ATA 8028 hotline and regional apps, have enhanced information access and market efficiency (Dhulipala *et al.*, 2024; Abate *et al.*, 2023). Yet, underutilization remains a major challenge due to poor connectivity, low digital literacy, and fragmented implementation (Gebreyes *et al.*, 2021). Integrating these platforms with cooperative-led marketing and government systems can improve adoption (Alemu & Koomen, 2023). Case studies reveal that localized training programs significantly increase digital tool uptake, demonstrating the need for context-specific approaches.

3.10. Value addition and agro-processing: Enhancing market linkages

Agro-processing initiatives, including Integrated Agro-Industrial Parks (IAIPs), have fostered clustering among processors, but infrastructure delays and governance challenges have limited their full potential (Boru *et al.*, 2024; Gebremariam *et al.*, 2024). Small-scale processing interventions coupled with technical training and innovative packaging have successfully increased income and market access, particularly for women (Mekonnen *et al.*, 2024; Endris *et al.*, 2024; Lemma *et al.*, 2008). These findings highlight the importance of context-specific interventions and inclusive approaches for scaling impact.

3.11. Access to finance: Overcoming barriers

Innovations such as mobile banking, warehouse receipt systems, and cooperative-led credit schemes have shown modest gains (Shikur, 2023; Abate *et al.*, 2023). Yet, risk-averse lending practices, stringent collateral requirements, and weak linkages with producer groups remain significant barriers (Duale, 2024; Devaux *et al.*, 2018). Empirical evidence from blended finance and government-backed guarantees indicates that addressing these systemic barriers enhances financial inclusion and scalability (Gebremedhin *et al.*, 2019).

3.12. Infrastructure development: Bridging regional gaps

Rural roads, storage facilities, and cold chains reduce transaction costs and post-harvest losses (Tesfaye *et al.*, 2023; Kassaye *et al.*, 2022). Regional disparities in investment, particularly in Gambella and Afar, limit equitable access to markets (Jembere *et al.*, 2023). Integrating digital platforms with infrastructure development can enhance last-mile delivery, highlighting the importance of targeted, context-sensitive investments.

3.13. Policy frameworks: Alignment and implementation

National and regional policies, including the Agricultural Transformation Agenda and IAIP strategy, have promoted commercialization, but weak coordination and top-down approaches limit their effectiveness (Kirina *et al.*, 2022; Vermeulen *et al.*, 2018). Successful interventions often feature strong institutional ownership and multi-stakeholder collaboration, underscoring the importance of policy coherence and alignment with local needs.

3.14. Limitations of the review

This review has limitations. First, publication bias may exist because only peer-reviewed studies in English were included. Second, regional data gaps, particularly from remote and emerging regions, may influence generalizability. Finally, some case studies lacked standardized reporting of effect sizes, which may have affected quantitative aggregation. Recognizing these limitations enhances transparency and guides cautious interpretation of the findings.

4. Conclusion and Recommendations

Systematic review of agricultural supply chains and market systems in Ethiopia has provided valuable insights into the complex challenges and innovative interventions that have emerged in the sector. The review identified several key themes, including the critical role of infrastructure development, access to finance, market information systems, and capacity building in strengthening agricultural supply chains.

The overall effectiveness of interventions in fostering systemic change has been constrained by ongoing structural and operational barriers. The need for a

comprehensive, integrated approach that addresses these barriers and builds upon the existing strengths of Ethiopia's agricultural sector is crucial for realizing long-term, transformational impact.

Policymakers should initially prioritize interventions that create foundational support such as infrastructure and financial access while concurrently building digital platforms and capacity. Strategic collaboration, policy coherence, and sustainability measures should follow to ensure long-term impact, with monitoring and adaptive management running continuously to mitigate unintended consequences.

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Design and Optimization of a Baffled Solar Cabinet Dryer for Mango Slices Using CFD Modeling

Ermias A. Tesema[1]*, Mulugeta A. Delele[2], Solomon W. Fanta[3], Fentaw B. Masrie[4], Melkamu Alemayehu[5], and Eneyw A. Tsegaye[5]

[1]College of Engineering and Technology, Mattu University, Mattu, Ethiopia
[2]Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam, Germany
[3]Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia
[4]College of Agriculture, Department of Food Science and post-harvest, Oda Bultum University, Oda Bultum, Ethiopia
[5]College of Agriculture and Environmental Sciences, Bahir Dar University, Bahir Dar, Ethiopia
*Corresponding author: ermiasa100@gmail.com

Abstract

Due to high production volumes, limited market access, and inadequate preservation technologies, postharvest mango losses remain a major challenge for smallholder farmers in Ethiopia, particularly during peak harvest seasons. This study aimed to design, optimize, and evaluate a baffled solar cabinet dryer for mango slices using Computational Fluid Dynamics (CFD) modeling. A cabinet solar dryer equipped with a rectangular baffled solar collector was designed, constructed, and experimentally validated. The CFD model showed good agreement with experimental data, with a relative humidity overprediction of 7.8% and a temperature underestimation of 4.35%. Key design parameters—including baffle configuration, inlet air velocity, and baffle cut percentage—were optimized to maximize outlet air temperature while minimizing pressure losses. Response Surface Methodology (RSM) integrated with ANSYS software identified the optimal configuration as four baffles with 25% cuts operating at an inlet air velocity of 1 m/s. The model was further extended to simulate moisture transport by incorporating the porous domain of mango slices. The experimentally determined effective moisture diffusivity was 5.224 × 10^{-7} m^2/s. Results indicated higher drying rates in the lower trays, confirming relatively uniform temperature and moisture distribution within the dryer. After two hours of drying, mango slice moisture content decreased from 45,942.17 mol/m^3 to 2,677 mol/m^3. Overall, the CFD model accurately predicted temperature, relative humidity, and moisture transport with minimal deviation. The optimized solar dryer provides a sustainable, cost-effective solution for reducing postharvest mango losses, thereby enhancing food security and improving smallholder farmer livelihoods.

Keywords: Convective heat transfer, Numerical simulation, Postharvest loss reduction, Smallholder-friendly technologies, Thin-layer drying

1. Introduction

For Ethiopian smallholder farmers, postharvest fruit loss—including that of mangoes—remains a serious problem. Due to inadequate preservation and processing methods during periods of high production, mangoes—which are prized for their nutritional

value and economic significance—frequently experience substantial waste. Food security and farmer livelihoods are significantly impacted by postharvest losses for perishable commodities, which can reach up to 40% in underdeveloped nations, according to reports (Prusky, 2011). By increasing efficiency and lowering reliance on fossil fuels, solar drying offers an economical and sustainable substitute for conventional techniques. However, problems including uneven temperature distribution, poor performance, significant energy losses, and inadequate airflow might restrict its efficacy and impact drying time and quality (Getahun, *et al.*, 2021). Computational fluid dynamics (CFD) is a powerful tool for examining fluid flow through dryers and thermal designs in both academic and industry contexts. Researchers are now able to build and modify solar dryers for better performance thanks to recent developments in Computational Fluid Dynamics (CFD) modeling. Drying conditions in solar dryers can be predicted and improved thanks to CFD's comprehensive understanding of heat and mass transfer phenomena. Research has shown that baffled solar collectors can improve temperature distribution and airflow, which will increase drying efficiency (Khanlari *et al.*, 2020). In order to overcome uneven drying and energy inefficiencies, this study uses CFD modeling to build and optimize a baffled solar cabinet dryer for mango slices. The results are intended to help food security in Ethiopia, improve mango preservation, and advance solar drying technologies.

The objectives of this study were to determine the optimal baffle configuration (number and cut) and air velocity to maximize outlet temperature and minimize pressure loss.

2. Materials and Methods

2.1. Dryer design, construction, and field experiments

The study was conducted in northwest Ethiopia at the Bahir Dar Institute of Technology, also known as Bahir Dar University. MDF wood, glass, sheet metal, black paint, and mesh trays were used in the construction of the solar dryer. A digital balance, Lux meter, anemometer, data loggers, PV system, colorimeter, refractometer, and caliper were among the tools. ANSYS Workbench 18.0 was used for CFD modeling. Several design equations, design constraints (environmental conditions), and general guidelines (collector and drying chamber sizing) were used to specify the dryer parts. According to Pawar *et al.* (1995), the ideal length-to-width ratio for a solar collector is between 1.5 and 2.5. For this investigation, the ideal value was 2, and the drying chamber's width, Wdc, was set to match the collector's width as depicted in figure 2.

2.2. CFD modeling and simulation of the solar cabinet mango slices dryer

In order to improve design and performance, accurate experimental representation, validation, and optimization are necessary for effective CFD modeling (Oberkampf & Trucano, 2002).

As indicated in Table 1, this study designed, modeled, simulated, and optimized solar cabinet dryers with different baffle numbers, baffle cuts, and air velocities.

Table 1: solar cabinet dryers with different baffle numbers, baffle cuts, and air velocities

Flat plate collector	Flat plate collectors with	
without baffle	Baffle cut	Number of baffles
	25%	2,4,6
	37.5%	2,4,6
	50%	2,4,6

The dryer's fluid movement was modeled using ANSYS CFX 18.1, and solar collectors with and without baffles were tested. A 3 mm porous medium was used to represent mango slices (Figure 1).

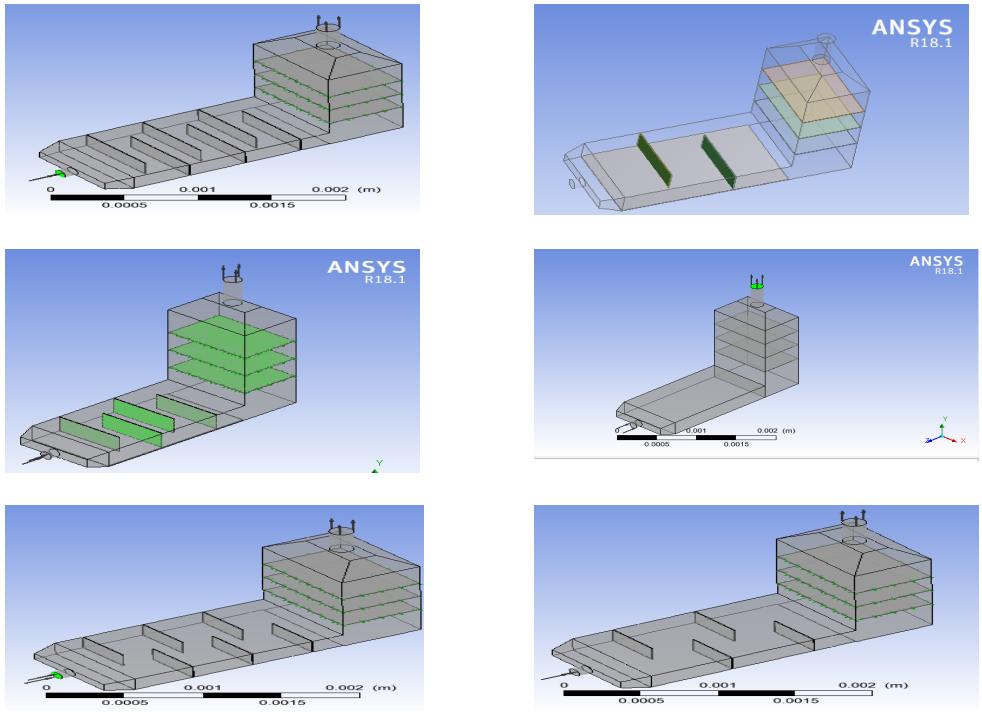


Figure 1: Solar cabinet dryers with 0, 2, 4, and 6 baffles with baffle cut of (25%-50%)

The standard Reynolds-averaged Navier-Stokes equations, along with equations 1-3 for energy transmission, were used to simulate the turbulent airflow in the drying system.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \text{Equation 1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) \nabla . (\rho \vec{v} \vec{v}) = -\nabla p \nabla . (\bar{\bar{\tau}}) \rho \vec{g} F \quad \text{Equation 2}$$

$$\frac{\partial}{\partial t}(\rho E) \nabla . (\vec{v} (\rho E p)) = \nabla . [-\vec{q} \sum j h j \vec{J} j (\bar{\bar{\tau}} e f f . \vec{v})] \quad \text{Equation 3}$$

Where,

$\vec{v}$= is the fluid velocity vector and

ρ = is the density of air

$\vec{F}$ = is the source term for momentum

E = is the total energy, $\bar{\bar{\tau}}$ = stress tensor

2.3. Geometry and meshing setup

The finite volume method was used to discretize the 3D model in Figure 2, and ANSYS-CFX was used to mesh it using tetrahedron elements, applying mesh refinement to cririical zones.

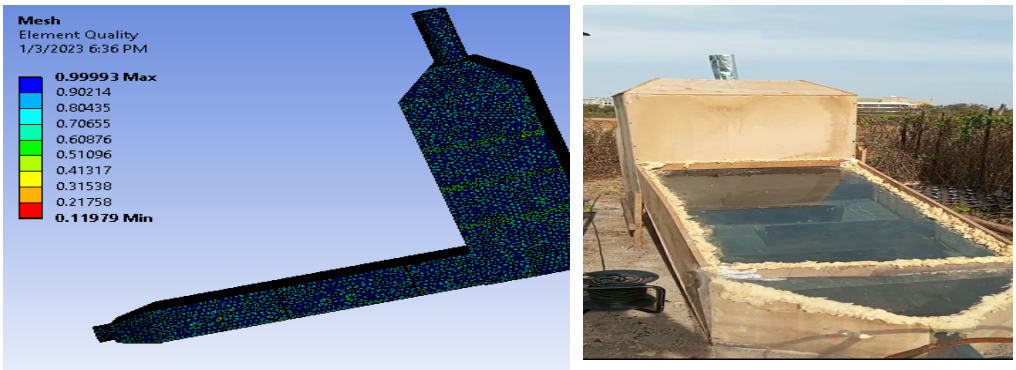


Figure 2: Meshing of the solar dryer and the constructed one

2.3.1. Model setup and boundary conditions

The boundary conditions for this investigation were established based on Bahir Dar's meteorological conditions and previous experimental data, which are compiled in Table 2.

Table 2: Model setup and boundary conditions

Parameter	Type	Value and unit
Solar radiation	Daily ambient	$-26.924t^2+279.54t+259.33$, $R^2=0.9827$
Inlet temperature (for transit simulation)	Ambient	$4e-8*t^2+0.0012*t+19.57$
Inlet air velocity	Normal	2m/s for experiment and 1-4(m/s
Wall	wood (MDF)	0.018m

Collector	sheet metal	0.008m
Glass	window glass	4mm, transparent
Baffle	sheet metal	0.008m
Porous(product)	Mango	3.88kj/ (kg k)

Turbulence model: The typical SST turbulence model, which is better appropriate for swirling flow, was employed among several turbulent models (Gorman *et al.*, 2016).

2.3.2. Sensibility analysis

The mesh independence results were displayed according to the outlet temperature since it was one of the most crucial intended simulation output results in this modeling.

2.3.3. Model validation

Equation 4 illustrates how the percent bias (PBIAS) statistics tool (Parajuli *et al.*, 2009) was used to validate the simulated result by comparing the outlet temperature of the model value with the experimentally measured value.

$$\text{PBIAS}=\frac{\sum_{i=1}^{N}(T_{expi}-T_{prei})*100}{\sum_{i=1}^{N}T_{expi}} \qquad \text{Equation 4}$$

2.3.4. Drying temperature, velocity, and relative humidity distribution

Using RANS equations, turbulence models, and extra expressions for p^sat and RH (equations 5 and 6), a CFD model was developed to simulate temperature, pressure, velocity, and relative humidity (Song *et al.*, 2012).

$$\ln(p_{sat}) = \mathrm{A} - \left(\frac{B}{T+C}\right) \qquad \text{Equation 5}$$

Where A, B, and C are constants specific to water (16.3872, 3885.70, and 230.170) respectively.

$$\mathrm{RH} = \left(\frac{P}{P_{sat}}\right) * 100 \qquad \text{Equation 6}$$

2.3.5. Optimization of the developed model

In order to enhance output temperature and decrease pressure drop, an optimal design based on air velocity, baffle cut, and multiple baffles was designed following parameter tests. The RSM optimization tool built into ANSYS software was utilized with this custom design.

Table 3: Optimization parameters and their levels

Parameter	Units	Levels	L1	L2	L3	L4
Velocity of air	m/s	4	1	2	3	4
Baffle cut	%	3	25	37.5	50	
No of baffles	N	3	2	4	6	

2.3.6. Modeling of Moisture Transport

In solar dryers, water vapor is treated as a scalar property, independently determining its mass transport with a general conservation equation, without influencing mass, momentum, and energy solutions for dry air.

$$\frac{\partial(\rho w)}{\partial t} = \nabla.(\rho \vec{u} w) = \nabla.(\rho D) + S_W \qquad \text{Equation 7}$$

Where w is the humidity ratio (kg water vapor/kg dry air), and D is the water vapor diffusion coefficient, which depends on temperature. The moisture transfer between mango slices and air during drying is represented by S_W Determined by equation 8.

$$S_W = Mw = A_{sv} h_m (C_e - C_a) \qquad \text{Equation 8}$$

The source term S_w Is added corresponding to the moisture transfer between the mango slices and air during drying. The equivalent water vapor concentration of the mango slices and the water vapor concentration of the air is given by the following Equations 9 (a and b).

$$C_e = \frac{M_w P_{sat} a_w}{RT} \quad (a) \qquad C_a = \frac{M_w P_{sat} RH}{RT} \quad (b) \qquad \text{Equation 9}$$

$$h_s = \frac{D_{eff}}{L_s}, \qquad \mathrm{RH} = \frac{\mathrm{Pa}}{\mathrm{Psat}} \qquad \text{Equation 10}$$

The overall mass transfer coefficient $\frac{1}{h_m} = \frac{1}{h_s}$ Where h_m=surface mass transfer coefficient(m/s) Asv is the ratio of the mango slice's surface area to volumeD_{eff} =5.224*10^{-7}m^2/s calculated from the previous experimental study (Tesema,2024). The moisture source term was determined based on the rate of change of moisture content during the drying process.

This rate is determined by the mass transfer coefficient (km) and the difference between the concentrations of water vapor in the surrounding air (Ca) and on the outside of mango slices (Ce). The saturation vapor pressure of free water is denoted

by pb, and the vapor pressure is denoted by pa. The saturation vapor pressure as a function of temperature was determined using the Antoine equation.

$$p_{sat}=exp\left(A-\frac{B}{T+C-273}\right) \quad \text{Equation 11}$$

2.3.7. Determination of mass transfer coefficient

the heat transfer coefficient was calculated using the Chilton–Colburn analogy for thermal and concentration boundary layers, as described Pasban *et al.*, (2017).

$\frac{D_{eff}}{k}$ K is mango thermal conductivity=0.925 W/m·°C Initial Moisture content (82.75%) in (mol/m^3) =MC=$\frac{MW}{Mmango}$, the initial moisture content of the product was calculated as 45942.17(mol/m^3) with a total of 6kg mango slices

3. Results and Discussion

3.1. Mesh independent study result

Meshing is crucial for accurate modeling, as results must remain consistent regardless of mesh size. To ensure precision, the optimal number of nodes and elements should be identified where further refinement does not affect the results.

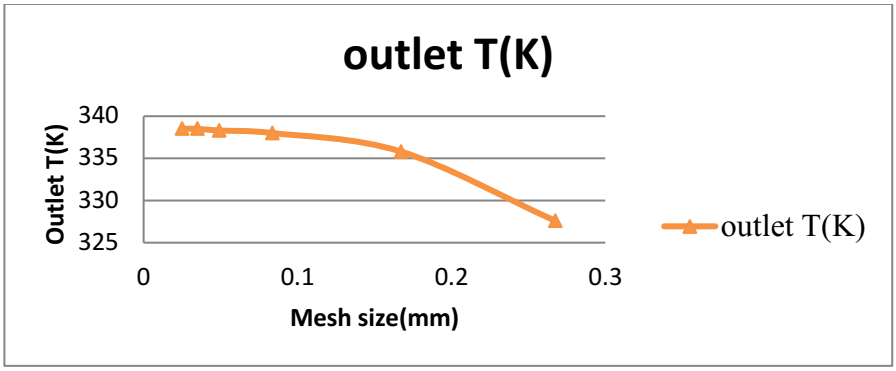


Figure 3: Mesh independent based on mush size on the outlet temperature

From the mesh independent study (figure 3), the mesh size with 0.048992mm and 82,793, 18,963 numbers of elements and nodes respectively were selected for further study.

3.2. Model validation

The CFD model overestimated the tray temperature by 2.176℃ (4.35%) compared to the experimental part of this research (Tesema, 2024) due to unaccounted heat losses.

The moisture distribution also underestimated the experimental value by 7.8%, as shown in Figure 4.

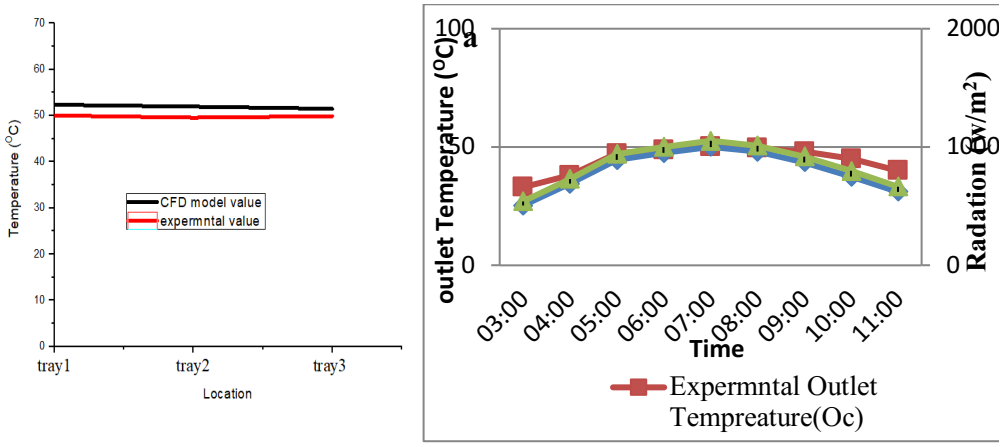
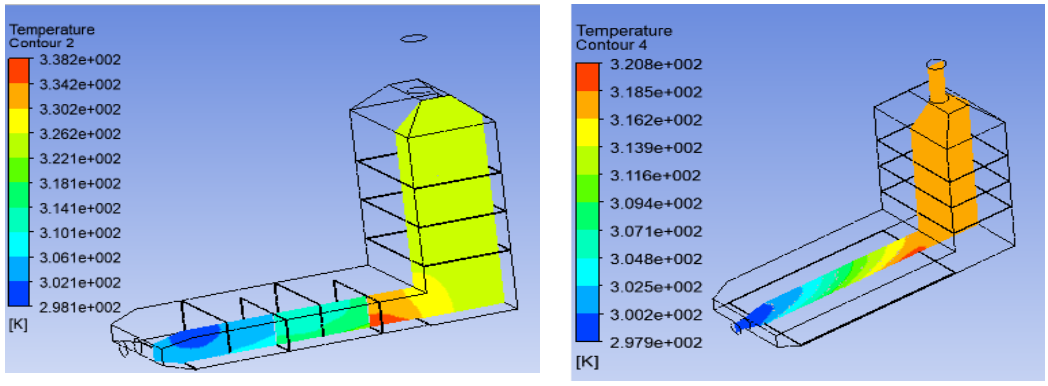


Figure 4: Validation graph based on the location of outlet T (°C) (a) and daily temperature variation (transit simulation) (b)

3.3. Pressure, temperature, and velocity distribution

Short drying times and uniform air velocity, temperature, and moisture distribution are essential for effective solar dryer operation (Getahun *et al.*, 2021). Temperature distribution and velocity streamlines are displayed in Figures 6-7. Maintaining consistent airflow within the drying chamber was made possible by a maximum velocity of 4 m/s and a pressure of 22 Pa. Because of the tiny cross-section, there was high velocity and pressure at the intake and outlet. The rectangular baffled solar collector in Figure 5 (a and b) increased thermal performance, as evidenced by the absorber temperature peaking at 338.2 K and tray 1 reaching 365.2 K.



(a) (b)

Figure 5: Temperature distribution inside the baffled collector and collector without baffle: a-collector with baffle, b-collector without baffle

The overall drying output temperature at the location of tray 1 was raised by 7.403°C (14%) compared to the non-baffled one, as demonstrated by the simulation results in Figure 5 for a solar cabinet dryer integrated with a rectangular baffle. enhances the air circulation inside the solar collector, which makes the energy transfer from the heated metal sheet to the humid air more effective. Solar cabinet dryers with rectangular baffles were used for solar dryer optimization based on this validation.

3.4. Velocity and temperature distribution

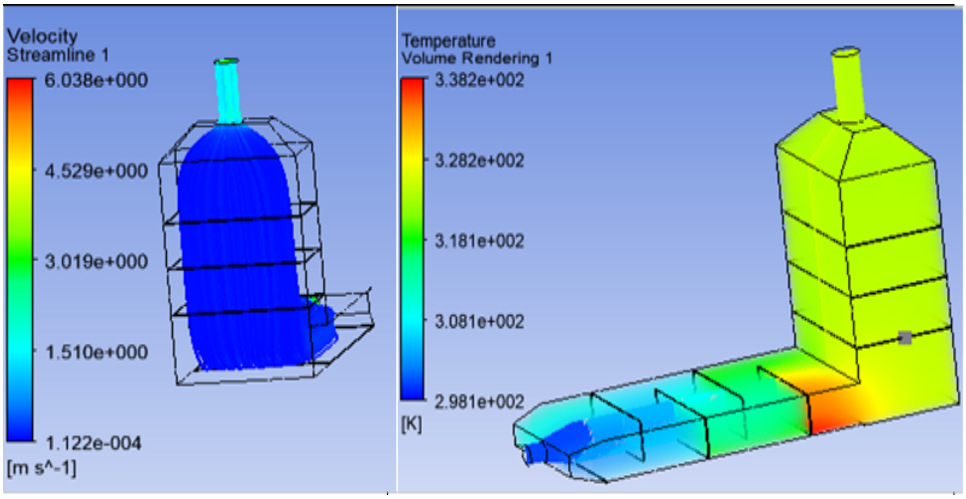


Figure 6: Velocity and temperature distribution on the designed solar dryer

With a little temperature change in the chamber, Figure 6 displays higher temperatures at the collector's bottom than close to the lid. According to Getahun *et al.* (2021), the CFD model showed an even dispersion of hot air (50–54°C), which helped produce mango slices that dried more quickly.

3.5. Relative humidity distribution

The amount of moisture in the air relative to its maximum capacity at a particular temperature is measured by relative humidity, or RH. RH varies as air flows through a baffled solar cabinet drier. The solar collector heats the ambient air at the input, increasing its moisture-holding capacity and reducing its relative humidity. The baffles properly distribute the hot air as it passes through the drying chamber. Its RH rises as the air absorbs moisture from the drying material, but because it begins with a low RH, it has a great capacity to absorb moisture. According to simulation results, the drying

chamber's relative humidity is approximately 17.5%, which is quite similar to the experimental value of 19%. RH is 1.5% underestimated by the CFD model, resulting in a 7.8% discrepancy. For parametric investigations, the model is deemed reasonably accurate because the error is less than 10%.

(a) (b)

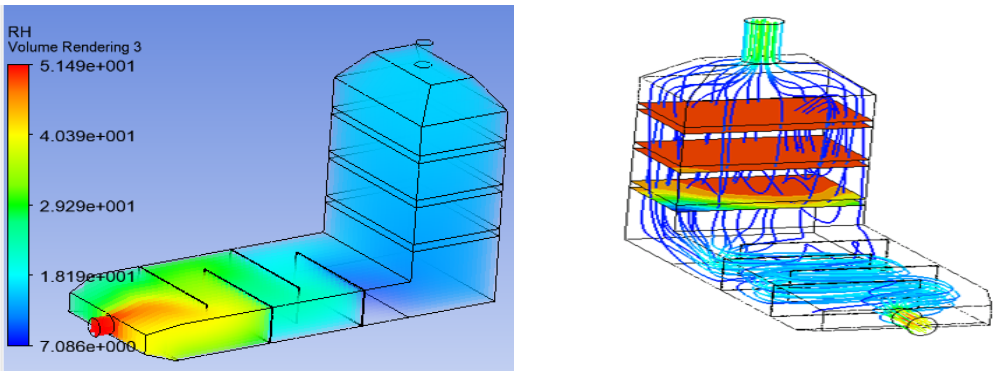


Figure 7: Relative humidity distribution inside the dryer (a: volume rendering, without loading, b: counterplot with mango slices loading)

3.6. Optimization of the dryer using the CFD model

Reducing drying time and enhancing product quality depend on the solar collector's outlet temperature. Reducing energy usage and guaranteeing economical operation require maintaining an ideal pressure drop. Regression model equation development:

Equations 12 and 13 offer model equations that relate process variables to pressure drop (2FI model) and outlet temperature (quadratic model).

$$Temperature(K) = 315.41 - 15.35 * A - 5.69 * B + 3.27 * C[1] - 1.64 * C[2] + 5.28 * AC[1] - 2.83 * AC[2] - 3.76 * BC + 18.7 * A^2 - 6.16 * B^2 \quad \text{Equation 12}$$

$$Pressure\ drop\ (pa) = 29.45 + 17.26 * A - 5.32 * B - 13.01C1 - 3.97 * C2 - 12.5 * AC1 - 4.88 * AC2 + 2.09 * BC \quad \text{Equation 13}$$

The regression model uses air velocity (A), baffle cut (B), and baffle count (C) to estimate temperature and pressure loss. The temperature rises with additional baffles and the interaction of A and C, but it falls with increased air velocity and baffle cut. Air velocity causes pressure drop to increase, yet fewer baffles and a larger baffle cut cause pressure drop to decrease. With C1 and C2 denoting binary interactions using six baffles as a reference, coefficients show the magnitude and direction of these impacts.

2.7. Study of desirability

Table 4: Constraints for optimization of the collector

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: velocity of air	is in range	1	4	1	1	3
B: Baffle cut	is in range	25	50	1	1	3
C: Number of baffles	is in range	2	6	1	1	3
Temperature	maximize	306	350.6	1	1	3
pressure drop	minimize	2.1	88.52	1	1	3

Table 5: Optimized solutions for combinations of numerical and categorical factor levels

Number	Velocity of air	number of baffles	baffle cut	Temperature	pressure drop	Desirability	Status
1	1.000	4	25	350.929	3.0896	0.994	Selected

Based on the optimization, it can be determined that putting the air velocity at 1 m/s, the number of baffles at 4, and the baffle cut at 25% produced the greatest response for achieving maximum outlet temperature and minimum pressure drop. With a maximum outlet temperature of 77°C at the collector's outlet and 58°C on tray 1, these parameters were determined to be the best ones for getting the intended result of the experiment.

2.8. Moisture distribution within trays

Flow, heat transfer, and moisture transport simulations were performed using the tray dryer unit's full geometry and mesh. Figure 8 depicted the simulated moisture distribution in the porous material after two hours of drying. Additionally, the convective air flow pattern causes the moisture content to rise from bottom to top. The top trays, which are farther from the heat source, may receive less heat and air flow than the first tray, which could cause the mango slices on the top trays to dry more slowly and have a higher moisture content.

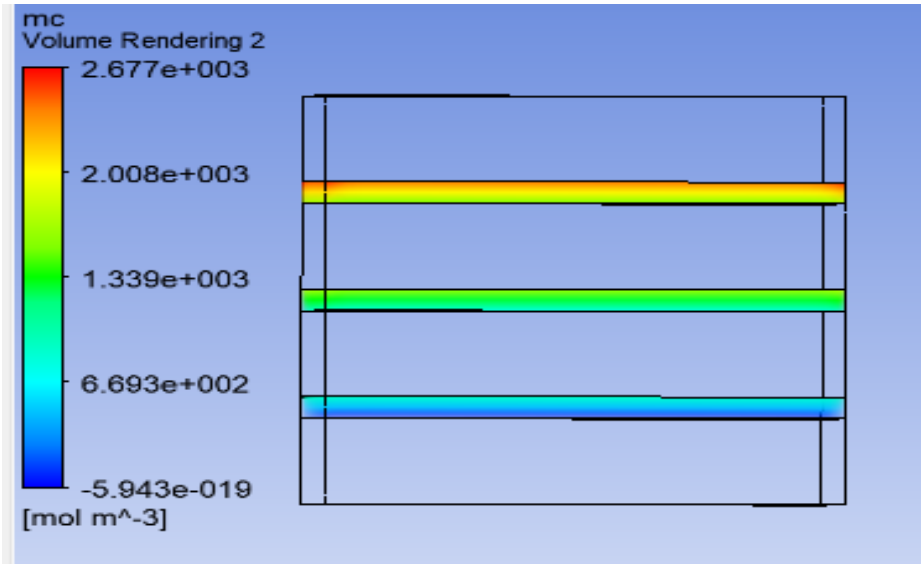


Figure 8: moisture content on the mango slices after 2 hours of simulation decreases from 45,942.17mol/m^3 to 2677mol/m^3 with 3mm thick mango

3. Conclusion and Recommendations

Using CFD modeling, the study improved airflow and heat transmission in a baffled solar cabinet dryer for mango slices. Important factors for maximizing thermal performance and minimizing pressure drop were air velocity (1 m/s), four baffles, and a 25% baffle cut. Mango slices were preserved and a long-term solution to postharvest losses was provided by the optimized drier, which successfully decreased moisture content. Reducing heat losses, expanding the dryer's capacity, and investigating its application to other perishable crops should be the main goals of future study.

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Impact of Real-Time Market Information on Smallholder Farmers' Decision-Making: The Case of National Market Information System

Solomon Tilahun*, Mirafe Marcos, Chimdo Anchala, Girum Ketema, Temesgen Gebeyehu, Yared Admasu, Mesfin Gizaw, Mulualem Ale, Alemayehu Manbegro, Dereje Regassa, Gizachew Nerea, Elsabet Tesfa and Haftamu Tesfay

Ethiopian Agricultural Transformation Institute (ATI), Digital Agriculture and Finance Directorate, P.O. Box: 708, Addis Ababa, Ethiopia
*Corresponding author: *Solomon.Tilahun@ati.gov.et; stlahun11@gmail.com*

Abstract

Digital agricultural solutions are increasingly enabling smallholder farmers to participate more actively in markets by improving their access to buyers and consumers, thereby enhancing profitability, livelihoods, and overall sector performance. Central to this transformation is a well-functioning agricultural market information system that can deliver timely, accurate, and accessible data to actors across the value chain. However, in Ethiopia, such systems have historically been underdeveloped, limiting access to reliable market information for key stakeholders. To address this gap, the Ethiopian Agricultural Transformation Institute, in collaboration with the Federal Ministry of Trade and Regional Integration, the Ministry of Agriculture, the Ethiopian Cooperative Commission, and their respective regional bureaus, developed and implemented the National Market Information System (NMIS). This study draws on secondary data from a range of published and unpublished sources and employs descriptive statistical methods to present findings through figures, charts, and tables for enhanced clarity. The paper examines the development, implementation, and outcomes of the NMIS, with particular attention to its role in improving market access, enhancing price transparency, and supporting data-driven decision-making among smallholder farmers and other stakeholders in agricultural commercialization cluster regions. The findings indicate that the NMIS has significantly expanded access to and use of market information, reaching over 1.6 million users, while also contributing to improvements in data collection and validation processes. The study concludes by highlighting the system's strong potential for scaling and its critical role in advancing agricultural transformation in Ethiopia.

Keywords: Agricultural markets, Digital Agriculture, ICT-based solution, Market Access, 6077

1. Introduction

Agricultural innovation and access to digital agricultural solutions have the potential to boost productivity, enhance market access, and improve agricultural services while simultaneously reducing negative footprints in agricultural value chains. Digital agricultural solutions help smallholder farmers become more active market participants by enabling them to reach marketplaces and consumers, ultimately leading

to higher profits, improved livelihoods, and a more efficient agricultural sector (Gebre *et al*., 2021; UNDP, 2022). Among these solutions, an Information Communication Technology (ICT)-based market information system plays a crucial role in providing timely, accurate, and reliable market data to all stakeholders, including farmers, buyers, retailers, planners, and government agencies. However, value chain actors in Ethiopia have not been able to access such market information due to the absence of a well-designed ICT-based market information system.

Particularly, smallholder farmers cultivate 95% of the arable land and contribute 90% of the country's total agricultural production. As a result, they play a significant role in driving agricultural growth and have been identified as key players in agricultural transformation, economic development, and meeting the country's rising food demand (Haile *et al*., 2022). Despite their importance, Ethiopia's agricultural sector faces persistent challenges, including fragmented markets, information asymmetry, and limited access to timely and accurate market data. These barriers hinder the sector's growth and disproportionately affect smallholder farmers, who make up a substantial share of the agricultural workforce.

To address this gap, the Ethiopian Agricultural Transformation Institute (ATI), in collaboration with the Ministry of Trade and Regional Integration (MoTRI), the Ministry of Agriculture (MoA), the Ethiopian Cooperative Commission (ECC), and their regional affiliates, has developed and implemented the NMIS (ATI, 2024a). By leveraging ICT, the system aims to bridge the information gap and empower agricultural value chain actors by providing timely, accurate and reliable market information for making informed decision (ATI, 2024). Specifically, the NMIS provides a comprehensive platform for collecting, validating, and disseminating timely, accurate, and reliable market information to farmers, traders, policymakers, and other key stakeholders.

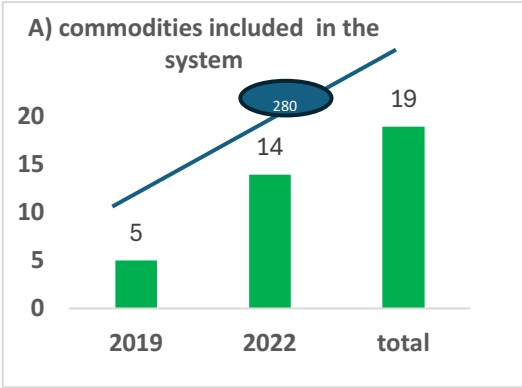
Therefore, the objective of this report is to assess the contribution of the NMIS to smallholder farmers' decision-making in Agricultural Commercialization Cluster (ACC) areas. Furthermore, it seeks to identify existing gaps that need to be addressed for the system's expansion, ensuring broader geographic coverage, inclusion of more commodities, and alignment with market requirements.

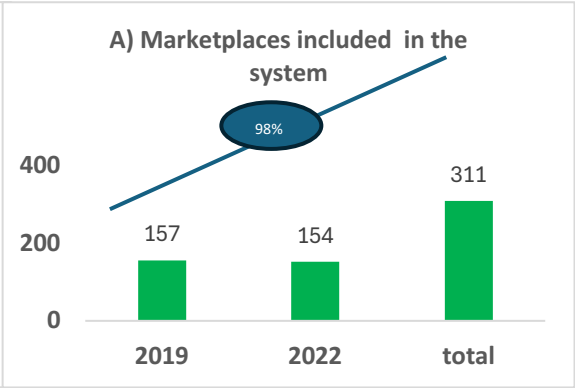
2. Materials and Methods

2.1. Implementation sites

The National Market Information System project was implemented across 311 marketplaces located within seven regions of Ethiopia: Amhara, Oromia, Tigray, Sidama, South Ethiopia, Central Ethiopia and Southwest Ethiopia. The expansion in system coverage is shown in Figure 1. A significant portion of these marketplaces, specifically 85%, were situated within the ACC woredas while the remaining 15% served as reference marketplaces, located outside of the ACC woredas. These reference marketplaces play a crucial role for smallholder farmers to make informed decisions

when quoting prices for their commodities, even if their own market is within an ACC woreda. The NMIS project's focus on both ACC and reference marketplaces aims to improve market transparency and access to information for smallholder farmers in all regions.





Source: System dashboard

Source: System dashboard

Figure 1. Number of Commodities (A) and Marketplaces (B) included in NMIS (April 2019 – 2022)

Woredas or marketplaces are chosen based on crop production potentials and national priority commodities for food security. Whereas commodities included in the system are selected based on information gap, economic potential, geographic coverage and export potential. The number of woredas or marketplaces allocated to each region was determined using the national budget allocation formula for regions where (Oromia 0.41%, Amhara 0.27%, SNNPR 0.23%, and Tigray 0.09%).

2.2. System design/model, approach and requirements

The system's design incorporates four key components or modules: Market data collection, validation, processing/analysis, and dissemination. Data collection methods include interviews, market observation, and triangulation with phone calls and secondary sources. The system employs a rigorous three-stage data validation process, including automated checks and geo-referencing, to ensure data accuracy. The collected market data is analysed in real-time, providing users with market trends, comparisons, and forecasts. Dissemination channels include Interactive Voice Response (IVR), Short Message Service (SMS), email subscriptions, and a web interface, catering to diverse user needs and preferences.

The project was designed to be implemented in phased approach, starting with a pilot in 2019 across 157 marketplaces in four regions of Ethiopia, focusing on 5 key agricultural commodities. The system was later expanded to cover additional 154

marketplaces and 14 commodities and reached a total of 311 marketplaces and 19 commodities, leveraging the Open Data Kit (ODK) mobile application for data collection by woreda-level government staff. In the third and fourth phases, the system will expand to include additional commodities, marketplaces, and requirements, ultimately evolving into a nationwide platform.

The first phase of the project focused on collecting basic market data, including price ranges (minimum and maximum) and supply volumes. Given the unstructured nature of many rural markets, precisely quantifying supply volume is often impossible. Therefore, instead of numerical figures, supply volume data was categorized qualitatively into three classifications: 'sufficient,' 'undersupply,' and 'oversupply'.

2.3. Data collection and analysis

This report is based on secondary data obtained from various published and unpublished sources, including insights from a joint monitoring visit conducted by ATI, terminal reports from the ACC program, an impact assessment of the project, performance reports, and data from system dashboards and the website. The collected information was analyzed using descriptive data analysis, with the results presented through charts and figures.

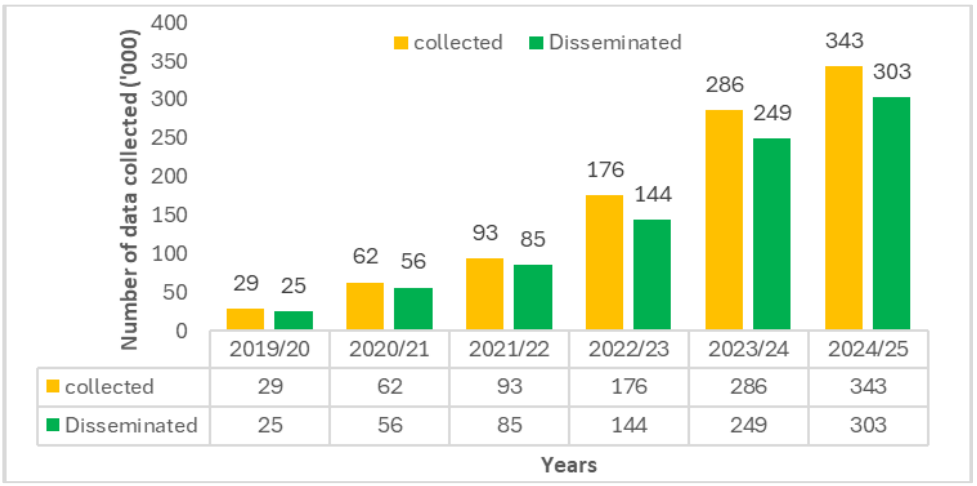
3. Results and Discussion

3.1. Contribution to ACC

The National Market Information System project is part of the ACC program and is designed to contribute to the program's objective of improving access to markets**.** It supports smallholder farmers by providing timely, accurate, and reliable market information, enabling them to secure better prices for their produce. Additionally, the system plays a vital role in tracking price trends and implementing mechanisms that help farmers obtain fairer prices for their products.

3.1.1. Improved the accessibility of accurate and reliable market information

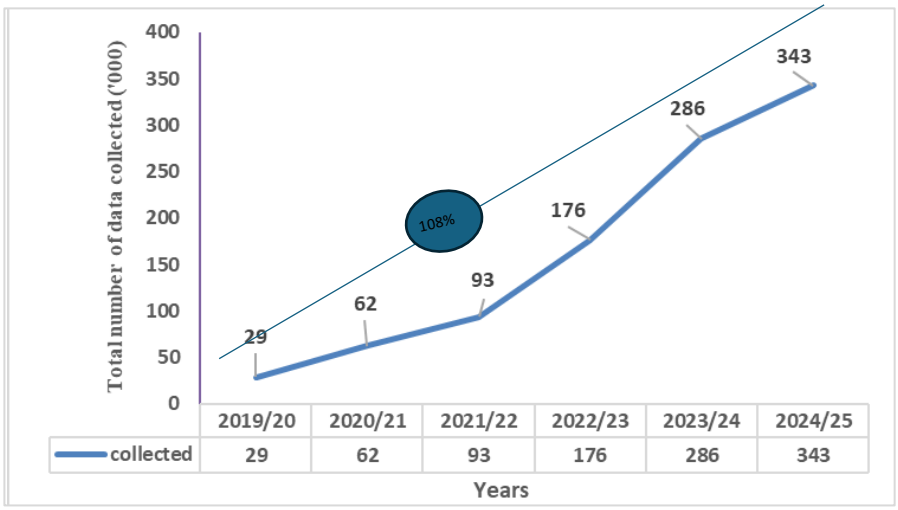
As of April 2019, the system has been collecting weekly market data on 19 commodities, including cereals, pulses, oilseeds, fruits, and vegetables, from 311 markets across the Amhara, Oromia, Sidama, Tigray, Southern Ethiopia, Central Ethiopia, and Southwest regions. Over 343,129 weekly data points on cereals, pulses, oilseeds, fruits, and vegetables were collected from all marketplaces (Figure 2). After undergoing a rigorous validation process, 303,641 (88.3%) were validated and disseminated to all users, including smallholder farmers, while 39,488 (11.5%) were rejected due to quality issues. As shown in Figure 2, the volume of data collected and disseminated has increased throughout the year.



Source: System dashboard

Figure 2. Number of market data collected, validated, and disseminated (April 2019 to January 2025)

Furthermore, the volume of weekly market data collected and verified annually has shown a significant upward trend over the years. In 2019/20, the number of data points collected was 28,798. This figure saw a substantial rise to 62,458 in 2020/21, marking an increase of more than twofold. As shown in Figure 3, the growth trajectory continued in the subsequent years, reaching impressive figures of 176,256, 285,734, and 342,585 data points in the 2022/23, 2023/24, and 2024 years, respectively. This consistent expansion highlights enhanced data collection efforts, improved validation processes, and a stronger commitment to market analysis over time. As of January 2025, the system stores over 304,532 validated market data points, establishing itself as one of the largest data sources for research and policy analysis

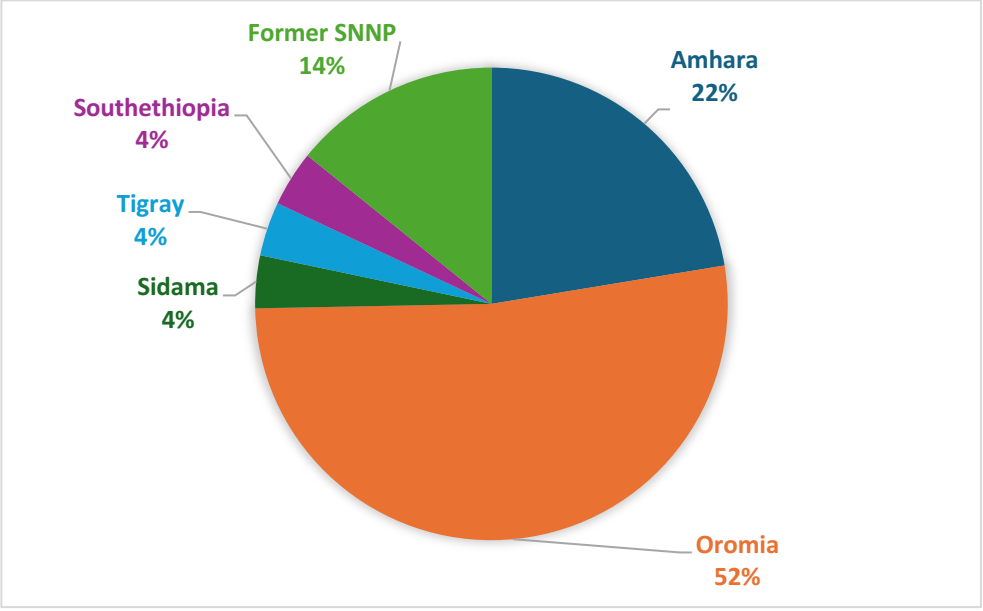


Source: System dashboard

Figure 3. Yearly growth of market data collected from all marketplaces since 2019/20

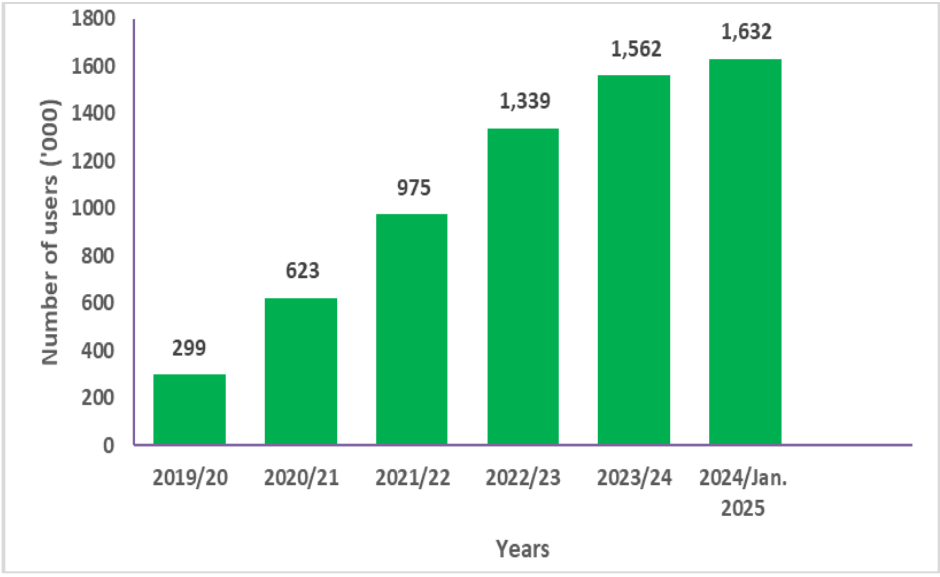
This demonstrates the consistency in data collection and validation efforts undertaken through collaboration between the project team and the regional trade bureaus. The consistency arises from the fact that the data enumerators are employees of existing woreda-level government staff, and the data collection is integrated into their regular job descriptions.

When we look at the regional distribution of data collection, the majority (74.5%) of data is collected from the two regions of Oromia (52.3%) and Amhara (22.4%) regions (Figure 4). The former SNNP region (excluding Sidama and Southwest) contributes 14.2% while the rest 3.8, 3.7and 3.6% is from Southwest, Tigray and Sidama regions. It is unsurprising that most of the data come from these two regions, as they are the major production areas for most of the selected commodities and serve as key market hubs. The ODK mobile application was used to transfer over 85% of the market data directly from the market to the central database online, while the remaining 15% was transferred offline and later entered by regional experts via the web. This was primarily due to prolonged internet blackouts caused by unforeseen circumstances such as conflict and other disruptions.



Source: Own computation sourced from system dashboard
Figure 4. The regional distribution of the collected market data

Since April 2019, over 1.65 million users, including 891,000 smallholder farmers, have registered and accessed the system to obtain verified market information through the IVR 6077 hotline, the website (www.nmis.et), and email (nmis@ata.gov.et) in Amharic, Afan Oromo, and Tigrigna. Users have made approximately 9 million calls to the IVR system, which provides information in these languages. Figure 5 shows the yearly distribution of registered users and calls made to access validated market information from the system. The steady increase in both the number of registered users and the number of calls indicates that users are receiving relevant information from the system.



Source: System dashboard

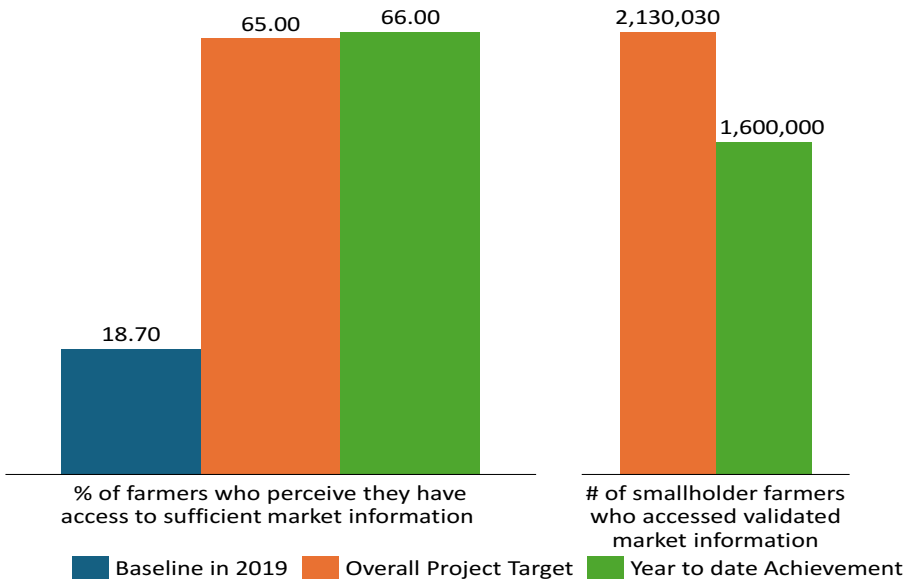
Figure 5. Number of Cumulative Registered Users as of April 2019.

3.1.2. Improved use of information for better decision-making

The NMIS has made remarkable progress in improving access to and utilization of market information, empowering a wide range of users with timely and validated information. To date, over 1.6 million users have registered on the platform, with smallholder farmers comprising 54% (approximately 864,000) of the total user base.

Among these smallholder farmers, more than 85% were actively engaged in ACC farming activities across the major program regions. By working in clusters, they benefit from shared knowledge, collective bargaining power, and improved efficiency in agricultural production. The system's impact is evident in the high level of engagement, as users have collectively made over 9 million calls to access verified market information through Interactive IVR 6077 technologies. This extensive usage underscores the growing reliance on NMIS for informed decision-making, contributing to greater efficiency and transparency in agricultural markets.

The contribution of the system is creating an improved access to market information and outlets for farmers in the ACC regions. According to the study conducted by ATI internal analytics team, compared to the baseline value, farmers' perceptions of their ability to obtain sufficient market information improved by 253%, rising from 19% to 66% of all farmers who participated in the study. Another key indicator reveals that 75% of the target (2,130,030) was achieved, with 1,600,000 farmers gaining access to validated market data for ACC commodities over the program's implementation period (Figure 6)



Source: ACC terminal report
Figure 6. The percentage of farmers who perceive they access to sufficient market information, and number of SHFs who accessed validated market information.

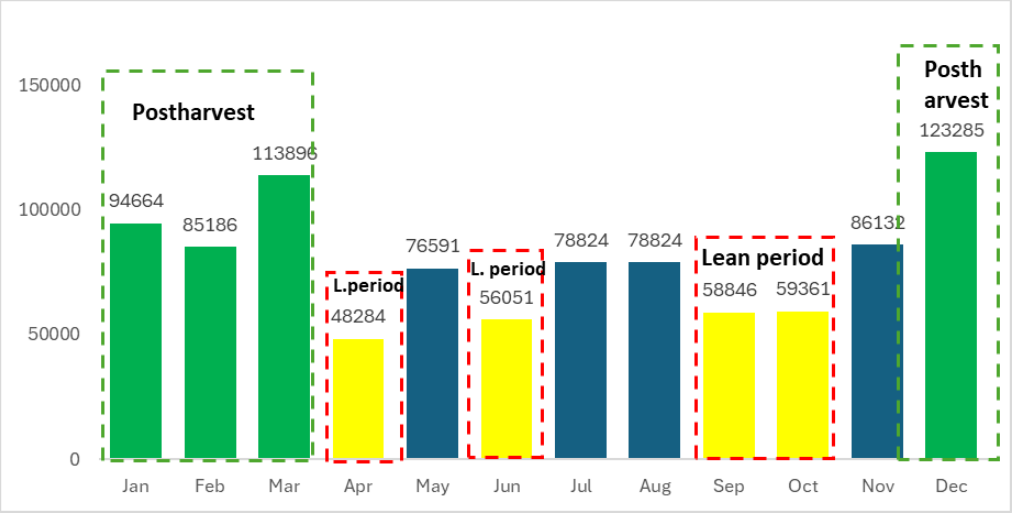
3.1.3. Influenced on Decision-Making

Farmers utilizing real-time market information demonstrate improved pricing strategies, better production planning, and enhanced bargaining power. Access to timely data allows them to adjust their market participation based on demand and price trends.

To further validate the effectiveness of the information obtained from the system, an impact assessment conducted by the ATI analytics team revealed that a significant majority of users find the NMIS to be a valuable tool for making price-related decisions. According to the findings of a joint monitoring visit carried out by the Program Monitoring, Evaluation, and Reporting (PMER) team, 54.5% of the respondents who

took part in the assessment confirmed that the price information provided by the NMIS reflects real-time market data. This timely and accurate pricing information has proven to be highly beneficial, as it enhances their ability to negotiate better prices and make more informed decisions during transactions.

One of the indicators of use by smallholder farmers is seasonal variation of information access. As shown in Figure 7, users' information demand corresponds to the seasonal production cycle of commodities included in the system. More users access validated market information using the 6077 short code during the postharvest period than during the lean period.



Source: Own computation sourced from system dashboard
Figure 7. Users accessing validated market information using 6077 per month (2022)

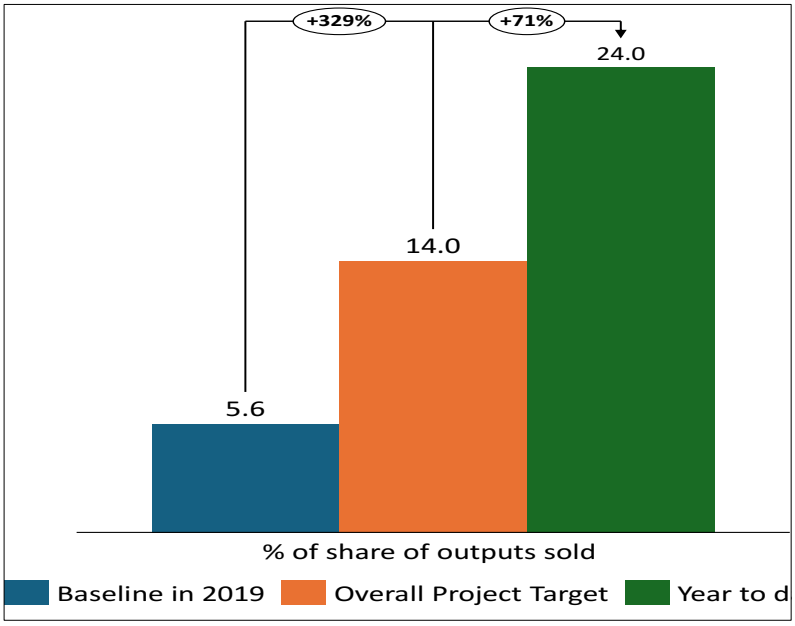
Beyond its direct impact on farmers, NMIS data has been utilized by other stakeholders, including the National Warehouse Receipt System (NWRS) and banks, for commodity valuation and loan assessments. Since year 2023/24, these banks have disbursed over 803 million Birr to customers without any defaults. They have also monitored loan statuses by analysing price trends displayed on the NMIS website. This highlights the system's potential for broader economic impact and its role in promoting financial inclusion within the agricultural sector.

3.1.4. Increased in marketable surplus

The NMIS project has made significant contributions to the results of the ACC intervention by offering farmers with timely, accurate, and relevant market information to support their decision-making and generate additional outlets for their marketable surplus. According to the ACC terminal report (2024), the marketable

surplus for five grain crops has significantly increased, now averaging 58%, which marks a 104% rise from the baseline value of 28.5%. This also surpasses the five-year target of 39.6% by 47%, highlighting notable advancements in agricultural productivity and market integration.

Likewise, the marketable surplus for five major horticultural crops—tomato, onion, avocado, banana, and mango—has grown by 9.71% from the baseline average of 64.08%, reaching 70.3% of total production. This progress indicates improved market access and value chain efficiency, ultimately boosting farmer incomes and fostering overall sector development. The proportion of marketable surplus sold increased from the five-year target of 14% (8,722,877 quintals) to 24% (15,229,985 quintals), surpassing the target by 71%. This marks a significant 329% rise from the baseline value of 5.6%. (Figure 8).



Source: ACC terminal report (2024)

Figure 8. Share of ACC outputs sold in comparison to the corresponding baseline values in 2019 and overall project target.

3.1.5. Improved access to markets

The NMIS has made notable progress in improving market access for producers by providing timely, accurate, and reliable market information to support informed decision-making. However, simply offering market data does not fully address the market access challenges faced by producers and other stakeholders. NMIS users have consistently requested a more advanced digital solution that goes beyond information

dissemination and facilitates direct connections between producers and potential buyers.

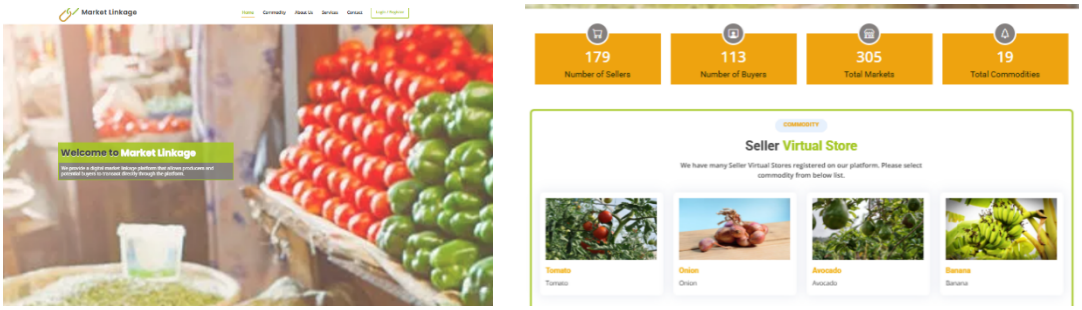


Figure 9. Prototype of the digital marketminkage platform

To tackle the issue, ATI collaborated with key federal and regional stakeholders developed and implemented a prototype of the digital market linkage platform as part of the NMIS system for a testing phase (Figure 9). Selected Producers Cooperative Unions (PCUs) in the ACC program regions and Consumer Cooperatives Unions (CCUs) in major towns of these regions received skilled training on commodity quality and the use of the platform. This was followed by a pilot transaction session, during which participants successfully conducted online transactions, facilitating the trade of over 600 metric tons through the platform.

However, the pilot implementation of the prototype revealed several critical gaps, necessitating a redesign to better align with user needs. These improvements focus on enhancing functionality, meeting technical and legal requirements, and improving overall user-friendliness. Based on this, an in-depth diagnostic study was conducted using internal capacity to gain a more comprehensive understanding of the current market linkage environment, the prevailing legal framework, and the available digital solutions. Besides, the development of a project design and system requirements documents are in progress.

3.1.6. Economic Effect

Access to real-time market information is associated with higher income levels and minimized losses through improved market timing (Zeleke and Wordofa, 2024). Many farmers in the ACC region who obtain price information from the NMIS gain access to profitable markets and enhance their negotiation power.

The results of the joint monitoring visit indicated that most of the farmers included in the assessment confirmed the crucial role of NMIS 6077. The system provides consistent and timely market updates, which significantly impact farmers' decision market timing, particularly in determining the most favourable time to sell their produce (ATI, 2024). By accessing real-time market information, farmers can optimize

their sales strategies, maximize profits, and reduce the risks associated with market fluctuations.

Accessing price information through the NMIS 6077 system has significantly influenced the income levels of farmers in the ACC regions as indicated in the ACC terminal report (ATI, 2024a). By providing timely and accurate market data, the system has empowered farmers to make informed decisions about when and where to sell their produce. This increased market transparency has helped farmers negotiate better prices, reduce exploitation by middlemen, and optimize their profits. As a result, the overall economic well-being of farmers in these regions has improved, fostering a more competitive and efficient agricultural market.

The ACC terminal report shows a substantial increase in farmer income, with households now earning an average of 27,001 Ethiopian Birr /ETB/ after accounting for inflation. This is a 20% increase compared to the program's baseline year (2019), demonstrating the positive economic impact of the ACC initiative on participating farmers. The NMIS has played a key role in boosting household incomes by offering timely, accurate, and reliable market information, enabling informed decision-making regarding selling of their agricultural products.

4. Conclusion and Recommendations

The NMIS has emerged as a crucial tool in addressing information gaps and promoting market efficiency in Ethiopia's agricultural sector. Its phased implementation, robust data collection and validation processes, and diverse dissemination channels have contributed to its success in reaching a wide range of users, including smallholder farmers. The system's impact is evident in its contribution to informed decision-making, improved market access, and enhanced price transparency.

The implementation of the NMIS has encountered multiple challenges from its inception to the present. Key hurdles have included high turnover rates among enumerators, which disrupt data collection; limited funding, affecting the system's sustainability and expansion; and a shortage of technical expertise. To ensure the sustainability of the project, the system relies on existing woreda-level government staff for data collection and entry. However, a major challenge has been the frequent turnover of data enumerators across marketplaces. This high turnover is largely due to the lower position grade level assigned to data enumerators compared to other experts at the woreda level.

As a result, during organizational restructuring, many enumerators either transfer to other departments for better opportunities or resign altogether. This has led to the loss of trained and experienced personnel, negatively impacting the quality and consistency of the collected data. The lack of continuity in skilled enumerators has posed a significant challenge to maintaining reliable market information.

The following are some of the key lessons drawn from the NMIS project implementation:

Strong linkage and coordination: Engaging key federal and regional project stakeholders from the beginning project design through to the current implementation phase has significantly contributed a lot to the project's success. The achievement of NMIS can largely be attributed to the effective collaboration and coordination among the various stakeholders involved in the project.

Incremental implementation**:** The NMIS is a ten-year project designed for implementation in four phases. It began with a limited number of commodities, marketplaces, and requirements in the initial phase, gradually expanding to include more commodities and marketplaces in subsequent stages. This phased approach allowed the project to adapt and improve based on lessons learned from each stage.

Use of existing government staff**:** the project leveraged existing woreda-level government data enumerators for data collection activity instead of hiring new enumerators. This approach was adopted to ensure long-term sustainability and foster a sense of ownership among regional bureaus, which will ultimately manage the system. By integrating data collection responsibilities into the existing regional structure, the project strengthens institutional capacity, reduces costs, and enhances continuity in implementation.

While the NMIS has made significant strides, continuous improvement and expansion remain crucial. Further efforts should focus on enhancing data accuracy, expanding commodity coverage, and strengthening user engagement to ensure the system's long-term sustainability and impact. The NMIS serves as a valuable model for other countries seeking to leverage ICT to transform their agricultural sectors and empower smallholder farmers.

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Transforming Livestock and Fisheries Extension through the Livestock and Fisheries Farmer's Field School (L&FFS) Extension Approach: Insights from the Ethiopian Agricultural Transformation Institute

Elias Abiyou, Yoseph Mekasha*, Zewditu Alemu, Yidnekachew Woldeyesus, Endeshaw Assefa, Zelalem Sisay, Getachew Animut, Sewinet Gebretsadik and Dagnachew Lule

Ethiopian Agricultural Transformation Institute, P.O.Box 708, Addis Ababa, Ethiopia
*Corresponding author: yoseph.mekasha@ati.gov.et

Abstract

This study assesses the short-term impacts of Ethiopia's Livestock and Fisheries Farmer's Field School (L&FFS) extension approach, a participatory and hands-on program aimed at empowering farmers to improve livestock and fisheries productivity. Guided by the Sustainable Livelihood Framework, which focuses on four key capitals—human, social, physical, and financial—the research evaluated outcomes among 270 households across four Ethiopian regions. Using a mixed-methods design, data were collected through household surveys, focus group discussions, and interviews, comparing pre- and post-intervention outcomes as well as comparing participating households with non-participants. Results demonstrate that the L&FFS approach significantly enhances farmers' livelihoods across multiple domains. Human capital improved markedly, with evidence-based decision-making rising from 1% pre-FFS to 90% post-FFS among participants and learning by doing reported by 95% of farmers. Adoption of climate-smart livestock practices increased from 87% to 93%, and the use of advanced technologies like artificial insemination and improved feed management exceeded 90% among FFS households, resulting in notable productivity gains such as increased milk yields and animal weights. Social cohesion and trust improved by 93%, and women's participation in decision-making reached 90%, promoting gender inclusivity and empowerment. Financial benefits included higher household incomes, with 93% reporting increased profits, and market linkage skills improved from 2% to 84%, facilitating better access to markets and income diversification. Overall, farmers expressed high satisfaction with the program, despite some challenges. The findings highlight that the L&FFS extension approach significantly enhances farmers' livelihoods across multiple livelihood domains, demonstrating its potential as a sustainable and participatory model for livestock and fisheries extension transformation. The study recommends scaling up the approach through enhanced capacity building, resource allocation, gender inclusion, and market linkages to ensure long-term impact and sustainability.

Keywords: *Capital domains, Extension, Livestock and fishery farmer field school, Transformation*

1. Introduction

Ethiopia's rural economy largely depends on smallholder agriculture, engaging about 85% of the population (MoA, 2015). Within this sector, livestock and fisheries play crucial roles, providing essential nutrients, employment, and income. However, productivity in these areas remains low, largely due to limited access to modern technologies, inadequate extension services, resource constraints, and the impacts of climate variability (Beyene *et al*., 2018). To address these challenges, innovative and inclusive approaches are needed ones that promote sustainability and empower farmers. One such approach that Ethiopia has increasingly adopted is the Farmer Field School (FFS) model, which originated in Indonesia in 1989.

The FFS emphasizes experiential learning, farmer-led innovation, and community participation, shifting farmers from passive recipients of knowledge to active learners and change agents (Khisa, 2004). Rooted in adult education and participatory learning theories, the model encourages critical thinking, problem-solving, and adaptability (Fenwick, 2001). Farmers learn best through observation, experimentation, and peer-to-peer exchange, which encourages critical thinking and adaptability to local conditions (Fenwick, 2001). This approach not only enhances farmers' practical skills but also fosters empowerment and sustainable practices. According to the FAO (1989), the core principles of FFS revolve around contextualized learning tailored to farmers' realities, ultimately strengthening their capacity to manage natural resources effectively and adopt innovative technologies. When implemented effectively, FFS can improve social cohesion, resilience, and behavioural change—factors essential for sustainable agriculture (Ngoma *et al*., 2018; Kaaria et al., 2007).

Globally, FFS has demonstrated considerable success across various agricultural sectors. In Indonesia, for example, FFS contributed to reducing pesticide use by up to half, while simultaneously boosting rice yields and pest control effectiveness (Khisa, 2004). In parts of Africa such as Kenya and Tanzania, FFS has enhanced farmers' knowledge of agroforestry, soil conservation, and climate-resilient practices (Kaaria et al., 2010; Kaaria *et al*., 2007). Ethiopia's experience with pilot FFS initiatives has also yielded positive results, including better soil conservation and strengthened community ties (JICA, 2012). Ethiopia has integrated FFS into its national strategies across various sectors, including natural resource management, pest control, and crop production (JICA, 2012). Furthermore, as outlined in Ethiopia's National Livestock and Fishery Extension Strategy, the L&F FFS is recognized as one of the primary modalities for extension service delivery across the country (MoA, 2022). More recently, the Ethiopian Agricultural Transformation Institute (ATI) in collaboration with stakeholders adopted the L&F FFS model across eight regions. It has expanded this model into the livestock and fisheries sectors, aiming to increase productivity, market access, and resilience. However, evaluations of the effect of this extension approach on livestock and fisheries sectors remain limited, often remaining qualitative or process-oriented rather than providing comprehensive, quantitative data.

The main objective of this study is, therefore, to evaluate the short-term impacts of the ATI's Livestock & Fishery FFS on smallholder farmers' livelihoods in Ethiopia using sustainable livelihoods framework (Scoones, 1998). Sustainable Livelihood Framework offers a useful lens to understand how extension services like FFS can bolster farmers' livelihoods. It views livelihoods as a combination of five interconnected assets: human, social, natural, physical, and financial capital. Specific objectives include assessing the effects on the four livelihood capitals—human, social, natural, and financial—and understanding farmers' satisfaction and perceptions of the L&F FFS services.

2. Materials and Methods

The Livestock & Fishery Farmer Field School (FFS) approach was implemented in high livestock potential areas of the country that predominantly has significant livestock value chains such as dairy, poultry, red meat, and fisheries. The program spans 58 woredas across nine regions, including Oromia, Amhara, Central Ethiopia, South Ethiopia, South-west Ethiopia, Tigray, Sidama, Benshangul-Gumuz, and Gambela. However, this study was narrowed to Oromia, Central Ethiopia, South Ethiopia, and Benshangul-Gumuz—areas identified for their high potential and active FFS implementation. This selective focus helps capture the most relevant impacts in regions where the program is most vibrant.

The study adopts a cross-sectional design to evaluate the short-term effects of the Livestock & Fishery FFS. It combines both quantitative and qualitative methods to build a comprehensive picture. Quantitative data was gathered through household surveys, providing measurable insights into changes across various livelihood indicators. Meanwhile, qualitative data was collected via focus group discussions (FGDs) and key informant interviews (KIIs), which offered deeper contextual understanding and insights from farmers, facilitators, and sector experts. This mixed-methods approach ensures that the study captures not only statistical shifts but also the perceptions and experiences of those directly involved.

To analyse the impacts, the study employs Scoones' (1998) sustainable livelihoods framework. This framework emphasizes four key capitals—human, social, natural, and financial—that influence livelihood outcomes such as income security, dietary diversity, resilience, and social inclusion. The evaluation centers on how participation in the FFS affects these capitals, thus providing a nuanced understanding of the program's influence on farmers' livelihoods.

Sampling was carefully structured to ensure representativeness. A multi-stage approach was used, starting with the purposive selection of 15 woredas based on geographic diversity and program maturity. Within these woredas, 15 kebeles and 27 FFS groups were purposefully chosen. From there, a simple random sampling technique selected 270 households—135 beneficiaries and 135 controls—ensuring gender balance and representation across key livestock commodities.

Data collection involved structured questionnaires administered through KOBO digital tools, with enumerators trained on proper protocols. FGDs and KIIs complemented this with qualitative insights, focusing on perceived benefits, challenges, and suggestions. Data analysis combined descriptive statistics with thematic interpretation, enabling a robust assessment of the program's short-term impacts and contextual factors shaping its outcomes. Quantitative data was analysed using descriptive statistics—frequencies, percentages, and significance tests—to evaluate change from Pre-FFS to Post-FFS, and the difference between FFS farmers and non-FFS farmers households. Qualitative data was thematically analysed to contextualize and deepen the understanding of quantitative findings. The integration of methods provided a comprehensive assessment of the program's impacts.

3. Results and Discussion

3.1. Socio-demographic characteristics

The demographic profiles of FFS and non-FFS farmers reveal notable similarities. Men predominantly make up both groups—63% of FFS farmers and 56% of non-FFS farmers—while women comprise 37% and 44%, respectively. Most farmers are young adults, with 58% of FFS farmers and 56% of non-FFS farmers aged between 21 and 35 years; older farmers over 55 are relatively rare, accounting for just 6%. Marital status is high across the board, with over 94% of FFS farmers and nearly all non-FFS farmers being married. Educational attainment differs somewhat: a significant majority of FFS farmers have completed high school (89%), with only 4% reaching tertiary levels. Conversely, non-FFS farmers display a broader educational background, with 16% having completed high school and a noteworthy 4% holding tertiary qualifications. Experience in livestock farming also varies—most FFS farmers have fewer years, with 19% in the 1–5-year range, while non-FFS farmers tend to be more seasoned, with higher proportions in the 6-10- and 11-15-year brackets. Overall, FFS farmers tend to be younger, less experienced, and more literate, whereas non-FFS farmers generally possess greater experience and higher educational diversity.

Table 1**.** Socio-dimorphic characterise of FFS Farmers and Non-FFS Farmers of respondents

Variables		FFS Farmers		Non-FFS Farmers	
		Frequency	%	Frequency	%
Gender	Male	85	63%	76	56%
	Female	50	37%	59	44%
	Total	135	100%	135	100%
Age	21 - 35	79	58%	76	56%
	35 - 55	48	36%	53	39%
	> 55	8	6%	6	6%
Marital status	Married	128	94.81%	131	97%
	Single	7	5.19%	4	3%

	Total	135	100%	135	100%
Educational Status	Tertiary	3	1%	5	4%
	High school	21	89%	21	16%
	Elementary	70	4%	47	4%
	Illiterate	41	4%	42	31%
Years in livestock farming	1-5	26	19.26%	13	10%
	6-10	24	17.78%	37	27%
	11-15	23	17.04%	30	22%
	16 or over	62	45.93%	55	41%

3.2. Impacts of L&F FFS on Capital Domains: Farmer's Perception

This section presents the findings derived from the analytical framework used to assess the short-term impact of Livestock & Fishery Farmer Field Schools (L&F FFS) on farmers' perceptions across the four capital domains. A comprehensive analysis of the results indicates that participation in L&F FFS significantly enhances farmers' capabilities, contributing to sustainable development outcomes. Notably, these improvements are evident when comparing farmers' perceptions before and after participation (pre- versus post-FFS), as well as between participants and non-participants (with versus without FFS).

3.2.1. Impact of L&F FFS on Human Capital: Knowledge, Skills, and Behaviour Change

The impact of L&F FFS on human capital development among farmers is quite remarkable. Before participating in FFS, most farmers had limited hands-on experience and problem-solving skills. Data shows that nearly none of them reported a high level of 'learning by doing'—the figure was effectively zero (see table 2 below). However, after engaging with FFS, this number surged to around 95%, indicating a significant boost in experiential learning ($p=0.001$). Similarly, problem-solving abilities, which are essential for adapting to changing conditions, rose from just 1% at high levels pre-FFS to 89% post-participation ($p=0.002$). The shift toward evidence-based decision-making was equally dramatic: only 1% of farmers relied on scientific or contextual evidence before FFS, but this jumped to 90% afterward ($p=0.005$). Additionally, awareness of household nutrition practices improved drastically, with 96% of farmers incorporating such practices post-FFS, compared to negligible levels earlier.

When comparing FFS participants with non-participants, the differences become even starker. Farmers involved in FFS consistently demonstrate higher levels of practical knowledge and skills. For instance, 95% of FFS farmers exhibit 'learning by doing,' compared to just 4% of non-participants ($p<0.005$). Similarly, 89% of FFS farmers showcase strong problem-solving skills versus 1% in the non-participant group, and evidence-based practice adoption stands at 90% versus 4%. Household nutritional awareness follows the same pattern, at 96% compared to just 1% among non-participants. These disparities underscore FFS's effectiveness in fostering experiential learning, critical thinking, and holistic household management. The study highlights the

significant impact of the Farmer Field Schools (FFS) on bridging the gender gap in human capital development. The result reveals L&F FFS significantly boosts women's human capital, increasing confidence, problem-solving, and leadership. Empowerment soared from 5% to 94%, and women's influence in livestock activities grew from 81% to 90%. This demonstrates how FFS enhances women's agency, aligning with Kabeer's view (1999) of empowerment as expanding their capacity to act.

Therefore, the findings support the Sustainable Livelihoods Framework by showing how experiential learning boosts human capital through practical skills like problem-solving and evidence-based decisions (Chambers & Conway, 1992; Scoones, 1998). These improvements align well with adult learning theories. Knowles (1984) emphasizes that self-directed, experiential learning boosts motivation and retention, while Kolb's (1984) cycle—focused on concrete experience, reflection, and experimentation—resonates with FFS methodologies. In addition, theoretically, it underscores participatory learning's role in livelihood resilience (Knowles, 1984; Kolb, 1984). Overall, these findings suggest that structured, participatory learning models like FFS can profoundly transform farmers' knowledge and behaviour, ultimately promoting resilience and sustainability in farming practices.

Table 2. Impact of L&F FFS on human capital

Human Capital Indicators	Rate	Pre-FFS		Post-FFS		Non-FFS		FFS	
		Frequency	%	Frequency	%	Frequency	%	Frequency	%
Learning by doing	Low	128	95	0	0	122	90	0	0
	Medium	7	5	7	5	8	6	7	5
	High	0	0	128	95	5	4	128	95
Problem solving skills	Low	128	95	0	0	114	84	0	0
	Medium	6	4	15	11	19	14	15	11
	High	1	1	120	89	2	1	120	89
Evidence-based decision practices	Low	130	96	1	1	125	93	1	1
	Medium	3	2	12	9	5	4	12	9
	High	2	1	122	90	5	4	122	90
Household nutrition	Low	127	94	1	1	111	82	1	1
	Medium	8	6	4	3	22	16	4	3
	High	0	0	130	96	2	1	130	96

3.2.2. Impacts of L&F FFS on Physical Capital: Knowledge, Technology Adoption, and Productivity

The study findings show that the influence of the L&F FFS on physical capital—particularly in terms of technical knowledge, technology adoption, and productivity—

appears both substantial and encouraging (Table 3) . Prior to participation, 95% of farmers exhibited low levels of climate-smart livestock and fishery knowledge, with none reaching high proficiency. However, after engaging in FFS, an impressive 93% of farmers attained high knowledge levels, a change that was statistically significant (p=0.001). Similar trends emerged in the adoption of improved farm technologies; initially, 93% of farmers had low adoption rates, but post-FFS, 91% achieved high adoption levels (p=0.001). This aligns with findings from Ngoma *et al*. (2018), who reported that participatory approaches like FFS increased technology uptake by over 30%, underscoring the platform's role in speeding up the diffusion of innovations.

Management practices, especially those related to feed and nutrition, also showed remarkable improvement. Before FFS, 96% of farmers had low adoption of improved feed management techniques. Post-participation, this figure dramatically dropped to just 7%, with 93% of farmers now demonstrating high adoption (p=0.001). Similar gains were observed in animal health management, where low adoption decreased from 98% to 10%, with the majority reaching high adoption levels (p=0.001). These shifts are crucial because improved management practices are linked to reduced livestock mortality and increased productivity, echoing FAO's (2009) emphasis on knowledge and practice as drivers of farm output enhancement.

When comparing FFS participants with non-participating farmers, the disparities become even clearer (see table 3 below). Non-FFS farmers predominantly remained at low knowledge levels (87%), while FFS farmers largely reached high knowledge levels (93%), with a significant difference ($p<0.005$). Similarly, technology adoption among non-participants was mostly low (82%), contrasting sharply with the high adoption rates (91%) among FFS participants. These observations are consistent with broader research, including Ngoma *et al*. (2018), who emphasize that participatory learning environments foster greater adoption of climate-smart technologies—an essential component of resilient farming systems.

Finally, the study result reveals that productivity outcomes further highlight L&FFFS's impact. Initially, 94% of farmers reported low productivity. After participation, 90% experienced high productivity levels (p=0.001). Comparing these figures with non-participants reveals that 83% of non-FFS farmers remained at low productivity, whereas 90% of FFS farmers achieved high productivity, driven by the adoption of improved breeds, better post-harvest practices, and climate-smart waste management techniques. The study also shows FFS participation improves women's physical capital, with 37% of FFS farmers being female compared to 44% of non-FFS farmers. Post-FFS, women reported significant gains in technical knowledge and technology adoption, reducing gender gaps and promoting economic resilience within the Sustainable Livelihoods Framework (Scoones, 1998). Collectively, these findings demonstrate that L&FFFS significantly accelerates farmers' technical knowledge, adoption behaviours, and productivity, ultimately contributing to more resilient and sustainable agricultural systems. The findings support the Sustainable Livelihoods Framework by illustrating

how participatory learning enhances physical capital—knowledge, technology adoption, and productivity—driving resilience and sustainability. They demonstrate that increased access to technical knowledge and improved management practices lead to greater innovation diffusion, consistent with FAO (2009).

Table 3. Impacts of L&F FFS on Physical Capital

Indicators for Human capital domain	Rate	Pre-FSS	Post-FFS		Non-FFS		FFS	
		Frequency	Frequency	Frequency		Frequency	%	Frequency	%
Knowledge and skills on climate smart livestock or fishery farming	Low	128	1	1	1	118	87	1	1
	Medium	7	8	8	6	11	8	8	6
	High	**0**	126	126	93	6	4	126	93
Adoption of improved technologies in L&F farming	Low	126	0	0	0	111	82	0	0
	Medium	8	12	12	9	23	17	12	9
	High	**1**	123	123	91	1	1	123	91
Adoption of improved feed and feeding management	Low	130	0	0	0	117	87	0	0
	Medium	5	10	10	7	16	12	10	7
	High	**0**	125	125	93	2	1	125	93
Adoption of improved animal health management practices	Low	132	0	0	0	124	92	0	0
	Medium	2	14	14	10	7	5	14	10
	High	**1**	**121**	**121**	90	4	3	121	90
Adoption of improved breed and genetic improvement practices	Low	129	1	1	1	116	86	1	1
	Medium	6	16	16	12	17	13	16	12
	High	**0**	**118**	**118**	87	**2**	**1**	**118**	**87**
Adoption of improved pre-and-post harvest practices in L&F farming	Low	128	1	1	1	115	85	1	1
	Medium	5	15	15	11	18	13	15	11
	High	**2**	**119**	119	88	2	1	119	88
Adoption of climate-smart wase management	Low	132	0	0	0	123	91	0	0
	Medium	3	11	11	8	10	7	11	8
	High	**0**	**124**	124	92	2	1	124	92

3.2.3. Impacts of L&F FFS on Social Capital: Trust, Networks, and Collective Action

Social capital plays a crucial role in fostering collective action, resource sharing, and community resilience, especially within rural development contexts. As the data in table 4 below clearly shows that participation in L&F Farmer Field Schools (FFS) significantly enhances farmers' social skills. Before joining FFS, almost all (93%) of farmers reported low communication skills, with none reaching high levels. Post-participation, this number flipped dramatically, with 92% achieving high communication competencies (p=0.001). Similar improvements are evident in conflict management, which shifted from 94% at low levels to 93% at high levels after FFS involvement (p=0.001). These findings are supported by Ngoma *et al*. (2018), who documented a 40% increase in effective communication among FFS participants, underlining the platform's effectiveness in encouraging dialogue and mutual understanding.

The study findings reveal that trust and social cohesion also saw remarkable growth. Initially, 93% trust was at low levels, but afterward, 93% of farmers reported high trust levels (p=0.001). Networking practices surged from negligible to 88% at high engagement levels (p=0.001). Farmers' capacity for teamwork improved slightly but meaningfully—from 93% at low to 94% at high levels. These social capital gains foster collective decision-making, resource mobilization, and conflict resolution, all vital for sustainable development, echoing the ideas of Putnam (1993) and Pretty & Ward (2001).

Comparing FFS participants to non-participants highlights the program's impact further. Non-FFS farmers had only 70% at low communication levels, whereas FFS farmers reached 92% at high levels (p<0.005). Trust levels among non-participants remained low at 76%, while FFS farmers reported trust at 93%. Similar disparities exist in networking and teamwork, illustrating how FFS promotes social bonds, trust, and collective efficacy.

In terms of empowerment and gender inclusion, participation, confidence, and public speaking skills all saw sharp increases due to the L&FFFS intervention. High empowerment levels among FFS participants jumped from just 5% to 94% (p=0.001). Women's involvement and influence also improved significantly—from 81% at low levels to 90% at high levels (p=0.001)—highlighting FFS's role in advancing gender inclusiveness and leadership, consistent with Kabeer's (1999) framework. Access to vital services like livestock support and markets also improved, with high access levels rising from 88% to 96% (p=0.001), facilitated by expanded social networks and trust. Therefore, the improvement in women's social cohesion fosters collective action, resource sharing, and advocacy, which are crucial for challenging traditional gender norms and establishing social legitimacy (Putnam, 1993). The increase in women's leadership and influence within groups directly contributes to their social status, positioning them as key actors in community development.

Overall, these findings confirm that the social capital benefits of FFS are substantial. Farmers develop stronger communication, trust, networks, and empowerment, which collectively underpin resilient, cohesive rural communities capable of sustainable development. The findings support the Sustainable Livelihoods Framework by showing how FFS enhances social capital—trust, networks, and empowerment—fostering collective action and resilience. This aligns with Putnam (1990) and Kabeer (1999), emphasizing social capital's role in sustainable rural development.

Table 4. Impacts of L&F FFS on Social capital

Social Capital Indicators	Rate	Pre- FFS		Post-FFS		Non-FFS		FFS	
		Frequency	%	Frequency	%	Frequency	%	Frequency	%
Communication skills	Low	125	93	0	0	94	70	0	0
	Medium	10	7	11	8	32	24	11	8
	High	0	0	124	92	9	7	124	92
Conflict Management Skills	Low	127	94	1	1	102	76	1	1
	Medium	8	6	8	6	28	21	8	6
	High	0	0	126	93	5	4	126	93
Trust and cohesion among farmers groups and service providers	Low	126	93	0	0	103	76	0	0
	Medium	9	7	10	7	25	19	10	7
	High	0	0	125	93	7	5	125	93
Networking Practices	Low	129	96	0	0	109	81	0	0
	Medium	6	4	16	12	22	16	16	12
	High	0	0	119	88	4	3	119	88
Team Working Practices	Low	126	93	1	1	112	83	1	1
	Medium	9	7	7	5	18	13	7	5
	High	0	0	127	94	5	4	127	94
Farmer empowerment status	Low	128	95	0	0	100	74	0	0
	Medium	7	5	8	6	29	21	8	6
	High	0	0	127	94	6	4	127	94
Women's empowerment Status (influence and participation in livestock farming & leadership)	Low	134	99	0	0	109	81	0	0
	Medium	1	1	13	10	21	16	13	10
	High	0	0	122	90	5	4	122	90

3.2.5. Impacts of L&F FFS on Financial Capital: Agribusiness management capacity and Livelihoods

The study highlights the significant impact of Livestock and Fishery Farmer Field Schools (L&F FFS) on farmers' financial capabilities, including literacy, management skills, access to financial services, income, and diversification (Table 5). Before participating in FFS, an overwhelming 95% of farmers exhibited low financial management skills. Post-FFS, there was a remarkable shif, 92% of farmers achieved high financial management skills (p=0.001). Similar trends were observed in entrepreneurial abilities, where only 5% displayed medium skills initially, but this soared to 92% after FFS engagement (p=0.001). Knowledge of marketing and market linkages also improved markedly, with high-level understanding rising from a mere 0% to 84%. Record-keeping and cost-benefit analysis skills showed comparable

progress, jumping from 0% to 86%. Additionally, utilization of financial services like savings and credit increased from 1% to over 94%, highlighting enhanced financial inclusion.

According to farmer's perception, L&F FFS has helped farmers to increase their level of income from livestock and fishery-related activities—high-income farmers increased from 0% to 93% (p=0.001). Diversification into multiple income streams also expanded, helping farmers reduce reliance on a single source and spread risk more effectively. Compared to non-participating farmers, who largely remained at low levels (85% at low management skills and 81% at low income), FFS participants showed clear gains, underscoring the program's role in fostering financial literacy, resource management, and economic resilience.

The data indicates that participation in FFS significantly narrows the gender gap on finical capital, with women's involvement in livestock and fishery farming business rising from 37% to 50%. This improvement aligns with the Sustainable Livelihoods Framework, which highlights how FFS enhances women's financial capital by improving management skills, increasing access to credit, and boosting income. These changes contribute to greater economic empowerment for women and help reduce gender disparities (Scoones, 1998).

Overall, these findings reinforce that L&F FFS significantly boosts farmers' financial literacy, management, and economic empowerment. Such improvements enable farmers to make better investment decisions, manage risks more effectively, and strengthen their livelihoods, aligning with prior research by Ngoma *et al*. (2018) and the World Bank (2008). Therefore, the findings align with the Sustainable Livelihoods Framework by demonstrating how FFS enhances financial capital—literacy, management, and income fostering economic resilience.

Table 5. Impacts of L&F FFS on Financial Capital

Financial Capital Indicators	Rate	Pre-FFS		Post-FFS		Non-FFS		FFs	
		Frequency	%	Frequency	%	Frequency	%	Frequency	%
Farm management & entrepreneurship skills	Low	128	95	1	1	115	85	128	95
	Medium	7	5	10	7	17	13	7	5
	High	0	0	124	92	3	2	0	0
Knowledge and skills in marketing information management and market linkage in livestock business	Low	132	98	0	0	122	90	132	98
	Medium	3	2	22	16	10	7	3	2
	High	0	0	113	84	3	2	0	0
Knowledge and skills and practice on record keeping and cost benefit analysis	Low	133	99	0	0	127	94	133	99
	Medium	2	1	19	14	6	4	2	1
	High	0	0	116	86	2	1	0	0
Financial services utilization practices (saving and credit)	Low	131	97	0	0	117	87	131	97
	Medium	3	2	8	6	15	11	3	2
	High	1	1	127	94	3	2	1	1
Income generating status from livestock and fishery business	Low	125	93	0	0	109	81	125	93
	Medium	10	7	9	7	22	16	10	7
	High	0	0	126	93	4	3	0	0
Engagement in more diversified income generating activities	Low	125	93	0	0	115	85	125	93
	Medium	10	7	10	7	18	13	10	7
	High	0	0	125	93	2	1	0	0

3.3. Farmer's Level of Satisfaction on L&F FFS Extension Service Approach

The survey results reveal a high level of satisfaction among farmers regarding the Livestock & Fishery Farmer Field Schools (L&F FFS) extension services. An impressive 94% of beneficiaries expressed overall satisfaction with the program's approach, with only a small minority (5%) feeling fairly satisfied and an even smaller percentage (1%) dissatisfied. When it came to the relevance and demand-driven nature of the training topics, 73% of farmers were satisfied, and 27% were fairly satisfied, with no respondents reporting dissatisfaction. Additionally, a substantial 73% of farmers appreciated the opportunities provided to experiment with different methodologies and technologies, while 26% felt fairly satisfied and just 1% were dissatisfied. These findings suggest that the L&F FFS extension services are effectively meeting farmers' needs, garnering strong approval, and demonstrating their relevance and effectiveness in supporting agricultural transformation (Table 6)

Table 6: Farmer's Level of Satisfaction on L&F FFS Extension Service Approach

Indicators used to measure LF FFs Services satisfaction level	**Frequency and %**		
	3*	**2***	**1***
Level of Satisfaction with the LF FFS extension services Approach	126 (94%)	6 (5%)	2 (1%)
Level of satisfaction regarding the relevance and demand-driven nature of the LF FFS training topics delivered	98 (73%)	37 (27%)	-
Level of satisfaction with the opportunity that the L&F FFS program provided to experiment with different methodologies and technologies	97 (73%)	36 (26%)	2 (1%)

3=Satisfied, 2=Fairly Satisfied, 1=Dissatisfied,

3.4. Challenges and Proposed Solutions for the Sustainability and Scalability of the L&F FFS Program

To evaluate the factors influencing the sustainability and expansion of the Livestock & Fishery Farmer Field Schools (L&F FFS) program, Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) were conducted with farmers, extension facilitators (Development Agents), and local experts at both kebele and woreda levels. The main challenges identified by participants include a general lack of awareness about the program's importance, which negatively affects stockholders' engagement and support. Dropout rates among participating farmers are also a concern, threatening the program's long-term viability. Additional barriers include resource limitations—such as shortages of stationery, insufficient incentives like daily allowances for facilitators, and inadequate transportation—hampering effective implementation. High facilitator turnover and limited active participation from trained master trainers further undermine the consistency and quality of program delivery.

In response, stakeholders proposed several strategic solutions. Ensuring adequate funding and resource allocation was emphasized to facilitate smooth operations. Providing sufficient daily allowances for facilitators was seen as vital for motivation and retention. Raising awareness at local institutional levels and integrating L&F FFS activities into existing extension services and planning cycles could foster greater ownership and sustainability. A particularly promising approach is to strengthen facilitator capacity through targeted

training of lead farmers within each group. These lead farmers could serve as peer trainers, equipping their peers with essential skills to continue and expand the program independently. This peer-led model not only builds local capacity but also reduces reliance on external facilitators, ensuring the program's sustainability and scalability.

Overall, implementing these strategies could lay a stronger foundation for the L&F FFS program, ultimately promoting its sustained growth and wider reach within the community.

3.5. Role of L&F FFS in Transforming the Livestock and Fishery Extension System

This study affirmed that the Livestock and Fisheries Farmer's Field School (L&F FFS) extension delivery model has proven to be a game-changer in how extension services support rural communities. By emphasizing hands-on, participatory learning, the program aligns well with adult education theories (Knowles, 1984; Kolb, 1984), which stress the importance of experiential, learner-centered approaches. This methodology not only deepens farmers' understanding but also helps them acquire practical skills and encourages lasting behavioural change. As a result, participation in FFS brings benefits across all key livelihood assets—human, social, physical, and financial—improving technical knowledge, fostering social bonds, and boosting economic resilience. This multifaceted impact supports broader frameworks of social capital and sustainable development, positioning FFS as a powerful tool for rural transformation.

Importantly, the L&F FFS approach has shifted extension from a traditional top-down model—where information flows from experts to farmers—toward a demand-driven, participatory system centered on farmers' needs. This shift has enhanced the relevance, uptake, and sustainability of climate-smart practices in livestock and fisheries, making extension services more effective and inclusive. Indicators of human capital, such as increased confidence, innovation capacity, and nutritional awareness, reflect these positive changes and are essential for building resilience in farming communities.

Overall, the L&F FFS program has redefined extension services, transforming them into more inclusive, impact-oriented platforms. Its influence goes beyond simply transferring technical knowledge; it promotes social cohesion and economic empowerment, both of which are vital for cultivating resilient, sustainable livelihoods. This approach exemplifies how participatory learning models can catalyse meaningful, long-term rural development.

4. Conclusion and Recommendations

The L&F FFS approach has markedly transformed Ethiopia's livestock and fisheries extension system by fostering participatory learning, enhancing farmers' technical skills, social cohesion, and economic resilience. Grounded in adult learning and social capital theories, it effectively shifts extension from top-down to demand-driven, promoting sustainable livelihoods. In addition, the L&FFS approach has the potential to catalyse gender equality through increased participation, social capital, and economic empowerment. Its success depends on deliberate strategies to address cultural and structural barriers, ensuring that women are not only participants but also leaders and decision-makers in rural development. The program's comprehensive impact underscores its potential to build resilient, innovative, and sustainable farming communities. Scaling and institutionalizing such models, with

emphasis on capacity building, resource allocation, and gender inclusion, are vital for long-term rural development and livelihood sustainability.

To ensure sustained impact, it is crucial to strengthen institutional support through increased resource allocation, capacity development of facilitators, and integration of peer-led training mechanisms. Expanding awareness campaigns and incentivizing facilitators can improve participation and reduce dropout rates. Additionally, fostering gender-sensitive approaches and enhancing market linkages will promote inclusivity and economic resilience. Embedding FFS within existing extension frameworks and policy support will facilitate scalability and long-term sustainability.

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Building Climate-Resilient Livestock Systems through Data-Driven Rangeland Monitoring: Insights from the Borana Rangelands, Southern Ethiopia

Yoseph Mekasha[1]*, Samuel Tuffa[1], Mohammed Abdulatife[1], Berhan Gessesse[2], Zerihun Cherie[2], Talema Moged[2], Gelana Daba[2], Gizachew Kabite[2], Wondemu Haimanot[2], Bireda Alemayehu[2], Bekele Bedada[2], Girum Ketema[1], Temesgen Gebeyehu[1], Kaleab Walelign[1], Ezedin Abdela[1], Dagnachew Lule[1], Belachew Tsihay[2], Abdissa Yilma[2]

[1]Ethiopian Agricultural Transformation Institute (ATI), P.O. Box 708, Addis Ababa, Ethiopia
[2]Remote sensing Department, Ethiopian Space Science and Geospatial Institute, Ethiopia
*Corresponding author: yoseph.mekasha@ati.gov.et | +251 913 112 203

Abstract

Ethiopia's rangelands cover about 61% of the national landmass and support over one-third of the country's livestock population, yet they are increasingly threatened by recurrent droughts, invasive species, and unsustainable land use. To address these challenges, the National Rangeland Monitoring System (NRMS) was established to generate standardized, spatially explicit, and temporally consistent data for assessing rangeland conditions and trends. The NRMS applies a stratified, multi-scale monitoring design integrating field-based biophysical measurements, remote sensing, and geospatial analysis. Although multiple indicators (vegetation, soil, water, livestock, and climate) are monitored, this paper focuses on vegetation, the key indicator of rangeland condition guiding livestock management. The study analyses herbaceous biomass data from grassland (GL) and woodland (WL) ecosystems in the Borana Zone, using fresh and dry biomass measurements. Data were managed through a digital platform supporting visualization, analysis, and decision-making at national and regional levels. Results show strong spatial variability linked to rainfall, grazing pressure, and management. Woodland sites had higher mean biomass and greater variability than grasslands, with fresh biomass of 710–8,670 kg/ha in WL and 350–6,970 kg/ha in GL, and dry biomass of 274–6,260 kg/ha in WL and 162–4,810 kg/ha in GL. Despite lower biomass, grasslands remain the main source of high-quality forage and are more vulnerable to grazing and climatic shocks. Overall, the findings highlight the value of NRMS for evidence-based rangeland governance, early warning, restoration targeting, and adaptive, climate-resilient livestock management through federal–regional collaboration

Keywords: Biomass, Borana, Climate resilience, Grassland sustainability, Rangeland monitoring

1. Introduction

Ethiopia's rangelands cover more than 60% of the national territory and characterized by arid and semi-arid agro-ecologies, experience a relatively harsh climate with low, unreliable and erratic rainfall (Fried *et al*., 2000). These regions own about 26% of the total livestock population of the country and are home for more than 12 million people whose livelihoods rely heavily on livestock production and related activities (Mossisa and Assefa, 2022). Rangelands are the major source of feed, which supports more than 60% of all ruminant livestock (Friedel *et al*. 2000). Ethiopian rangelands provide numerous goods and services that have great social, economic, cultural and biological values.

However, the rangelands of the country have been degraded at alarming rate due to increasing climate variability, poor grazing land management including over grazing, and weak institutional frameworks (Berry and Campbell, 2009). Degraded rangelands are characterized by reduced biological and economic productivity resulting from unsustainable land use practices. These pressures affect hydrological processes, soil functions, and vegetation composition (Belay and Siraj, 2024). Degradation leads to lower pasture production and encourages bush encroachment and the spread of invasive species, particularly in arid and semi-arid rangelands. As a result, livestock carrying capacity declines, biodiversity decreases, ecosystem structure is altered, and the provision of ecosystem services is reduced.

The Borana rangelands constitute a vast semi-arid ecosystem in southern Ethiopia and, until a few decades ago, were considered among East Africa's most productive and resilient rangeland systems. However, like many other rangelands, they have experienced significant degradation, leading to a decline in grassland cover and negatively affecting the livelihoods of pastoral communities (Abate and Angassa, 2016).

Addressing these challenges requires, in general, a robust monitoring system that provides reliable, spatially consistent, and temporally comparable data. A rangeland monitoring system is crucial for understanding rangeland health, guiding the sustainable management of livestock and rangeland resources, and ensuring the long-term sustainability of these ecosystems. Introducing a robust rangeland monitoring system is therefore essential for informed decision-making, preventing land degradation, and strengthening livelihoods.

In this context, the Ethiopian Agricultural Transformation Institute (ATI), in collaboration with the Ministry of Agriculture (MoA) and development partners, initiated the National Rangeland Monitoring System (NRMS). The NRMS aims to operationalize data-driven, evidence-based decision-making in rangeland management through integrated field monitoring, remote sensing, and digital analytics. Accordingly, this paper draws on insights from the Borana pilot study to enhance the national rangeland monitoring system's capacity to capture spatial variability in rangeland productivity and to provide evidence on vegetation dynamics directly relevant to livestock-based livelihoods.

2. Materials and Methods

2.1 study Area

The Borana rangelands of southern Ethiopia were selected as one of the pilot sites given their ecological diversity and socio-economic significance. The study was conducted in Borana Zone, Oromia Region, covering the districts of Yabello, Dire, Dhas, Miyo, and Dubluk (Figure 1). The area is characterized by bimodal rainfall, strong climate variability, semi-arid ecology, and a combination of grass-dominant plains and bush-encroached woodlands.

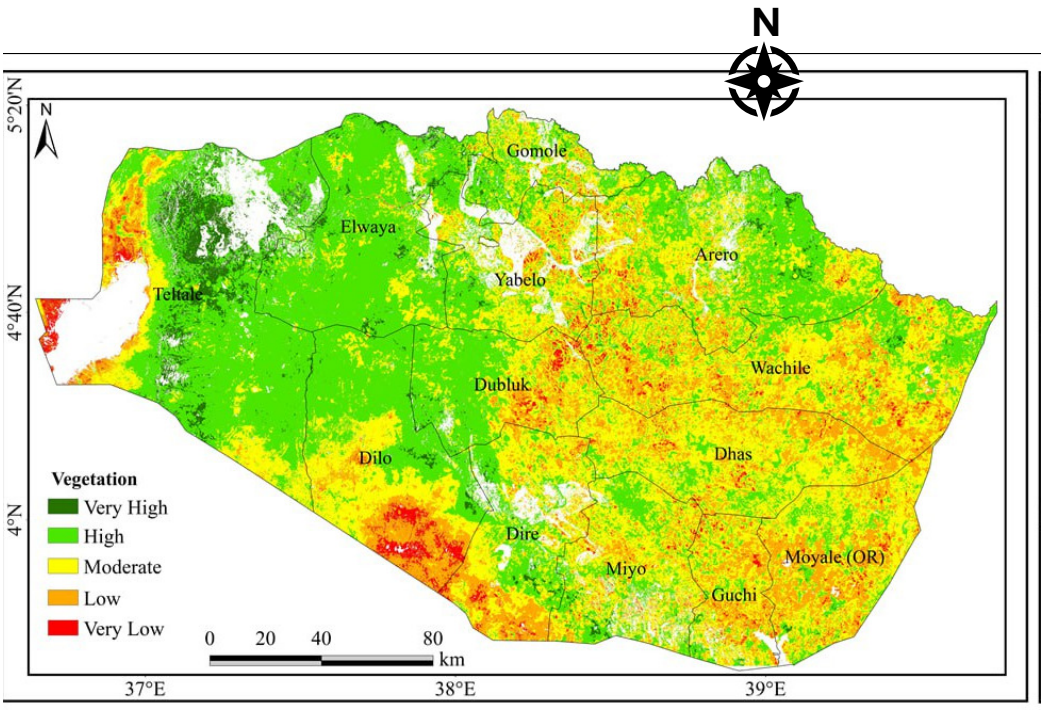

Figure 31: Geographic location of the NRMS pilot districts in the Borana rangelands

2.2 Data Collection

The NRMS framework (Figure 2) adopts a multi-scale and multi-indicator monitoring approach that combines biophysical field data, geospatial analysis, and digital data management. In this paper, however, we considered biomass as vegetation indicator as it is a major indicator of rangeland condition that dictates livestock management such as herd mobility based on the spatiotemporal variation in vegetation.

Field sampling employed a stratified random design across two main land types: Grassland (GL) and Woodland (WL). Within each land type, herbaceous vegetation biomass was measured through clipping and weighing in 1 m^2 quadrats across randomly selected plots. Fresh and dry biomass weights were recorded in kg/ha, and descriptive statistics were used to compare productivity across districts and land types.

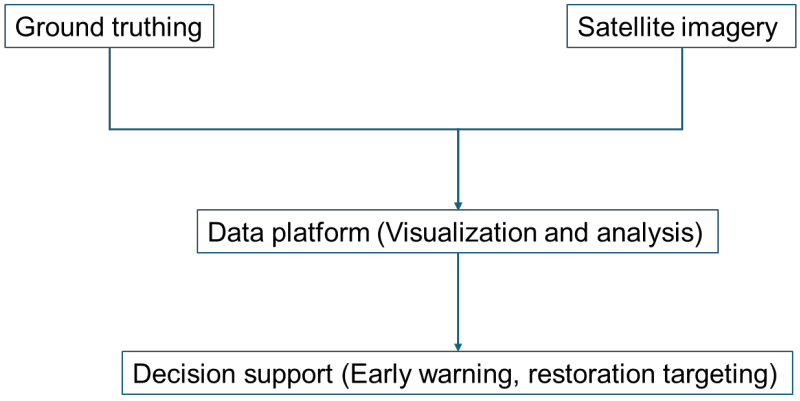

Figure 32: Conceptual framework of the National Rangeland Monitoring System (NRMS)

2.3. Data Analysis

Descriptive statistics and comparative assessments were conducted to characterize biomass differences across GL and WL land types. Variability was assessed using ranges, distributions, and interquartile comparisons.

3. Results and Discussion

3.1 Vegetation Biomass Dynamics in Borana Rangelands

The field-based assessment conducted under the National Rangeland Monitoring System (NRMS) revealed significant spatial variability in aboveground biomass across the Borana monitoring sites (Table 1). Mean total fresh biomass ranged widely among districts, reflecting differences in rainfall, vegetation composition, and grazing intensity. Higher biomass values were recorded in Dire and Dhas, areas known for relatively favorable rainfall distribution and better-managed enclosures, while lower values were observed in Miyo and Yabello, which are characterized by lower precipitation and heavier grazing pressure (Figure 3). This pattern aligns with the established aridity gradient of the Borana zone, confirming that climatic and management factors jointly determine vegetation productivity.

Table 15: Mean Dry Biomass by Land Type

Biomass Category	Mean (+STDEV) (kg/ha)	No. of Sites
Grassland (herbaceous)	2165 ± 1143	51
Woodland (under-canopy herbaceous)	2462 ± 1503	43
Woody biomass	1316 ± 652	43
Woodland Total Biomass	2903 ± 1537	94

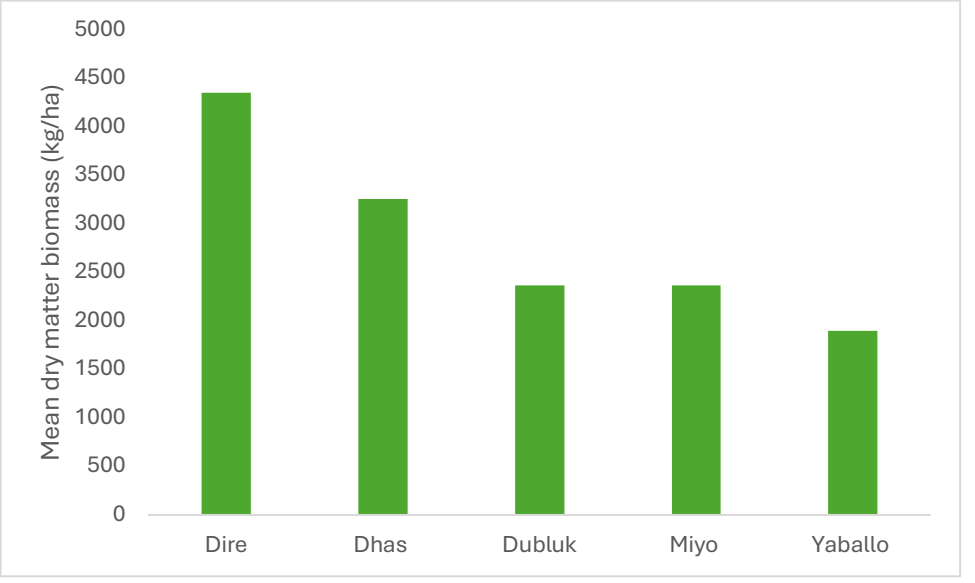

Figure 33: Mean Dry Biomass by district

3.2. Comparative Biomass Productivity Between Land Types

Figure 4 illustrates biomass variability between grassland (GL) and woodland (WL) ecosystems. Fresh biomass showed a broader distribution and slightly higher median values in woodlands, suggesting that herbaceous vegetation, primarily perennial grasses, dominates productivity during the growing season. In contrast, grassland sites exhibited more stable but generally lower fresh biomass. The substantially higher variability of woodland biomass than grasslands reflect heterogeneous under-canopy microenvironments, mixed woody–herbaceous vegetation layers and patchiness associated with variable light, soil moisture, and root competition.

Grassland biomass values were more tightly clustered, reflecting a relatively uniform herbaceous layer but also indicating higher vulnerability to climatic shocks, attributable to absence of woody plant association in grasslands and hence reduced grass cover outside of tree habitats.

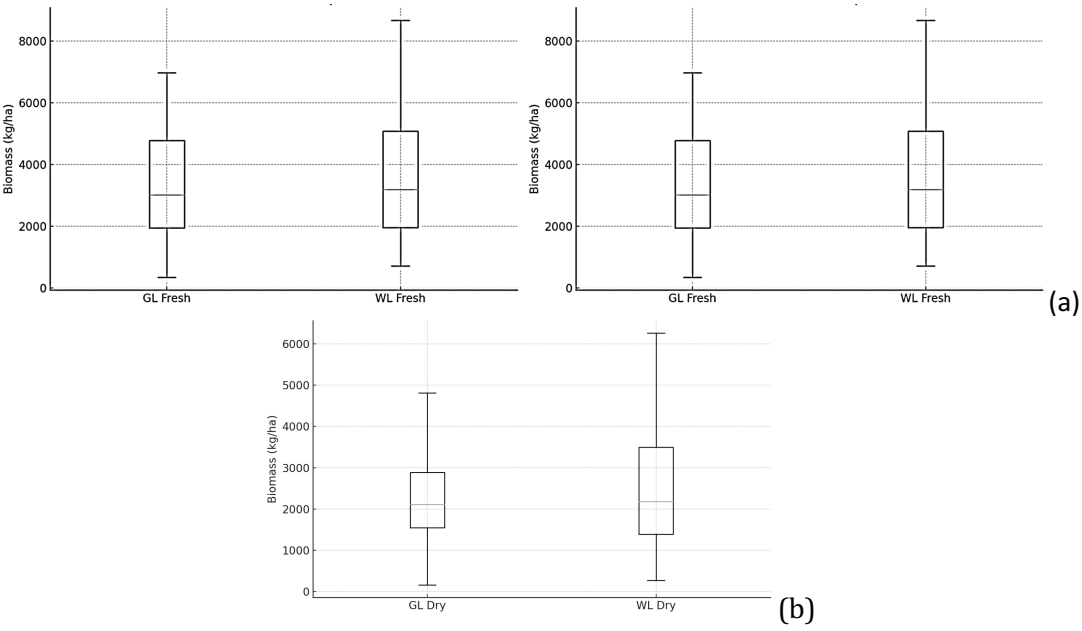

Figure 34: Total fresh (a) and dry (b) herbaceous biomass (kg/ha); *GL: Grassland; WL: Woodland*

Dry biomass displayed a somewhat reversed pattern: woodlands maintained relatively higher residual biomass, indicating greater aboveground standing matter contributed by woody shrubs and trees. This implies that while GL systems support rapid seasonal forage accumulation, they are more sensitive to overgrazing and rainfall fluctuations, whereas WL systems retain biomass longer, enhancing ecological persistence but contributing less to immediate forage availability.

These differences highlight the influence of rainfall distribution, rangeland management practices, and site-specific ecological conditions on rangeland productivity. The fresh biomass ranged around 350–6970 kg/ha in grassland sites, whereas dry biomass ranged between 162–4810 kg/ha depending on land type and district. Likewise, the fresh biomass ranged around 710–8670 kg/ha in under-canopy of woodland sites, whereas dry biomass ranged between 274–6260 kg/ha.

The observed patterns align with earlier findings that vegetation recovery and biomass accumulation in semi-arid rangelands depend strongly on rainfall gradients and grazing exclusion efforts (Daba and Mammo, 2024; Liao and Clark, 2018). The NRMS provides a structured and repeatable mechanism to monitor such variations, thereby supporting adaptive management strategies (Mekasha *et al*, 2025). Furthermore, integrating digital tools and spatial data analytics enhances early warning capabilities, improves restoration targeting, and facilitates decision-making for sustainable pastoral systems (Bayer., 2017).

3.3. Implications for Rangeland Productivity and Climate Resilience

The observed spatial and structural differences underscore the need for differentiated management strategies. Grasslands with high seasonal variability require mobility/rotational grazing and deferred use, while woodland areas may benefit from controlled bush thinning to improve herbaceous regeneration. These strategies are consistent with climate-resilient rangeland management principles that balance forage availability, ecosystem stability, and livestock carrying capacity.

The integration of these biomass measurements within the NRMS digital platform enables real-time visualization and trend analysis (Figure 2). This functionality supports evidence-based decision-making by local administrators, development practitioners, and policy planners. Over time, linking ground biomass data with remote sensing indicators will enhance predictive capacity for early warning of feed shortages and targeted restoration planning.

3.4. District-Level Variations and Restoration Targeting

The spatial distribution of biomass (Table 1) provides actionable insights for prioritizing intervention areas. Districts such as Dire and Dhas, with higher biomass potential, can serve as demonstration sites for sustainable intensification practices, while Yabello and Miyo represent critical districts for rangeland rehabilitation through reseeding, area closure, and community-based grazing management. Integrating these findings with socioeconomic and climatic data in subsequent NRMS cycles will strengthen the predictive understanding of rangeland dynamics under climate variability.

3.5. Broader Implications for Agricultural Transformation

The Borana pilot findings exemplify how data-driven monitoring can operationalize sustainable agricultural intensification and climate resilience in pastoral systems. By institutionalizing the NRMS within Ethiopia's rangeland governance framework, ATI and its partners are establishing a replicable model that links field ecology, digital analytics, and policy decision-making. This approach directly supports the goals of Ethiopia's Agricultural Transformation Agenda by enhancing livelihood resilience, resource-use efficiency, and adaptive management capacity in dryland production systems.

4. Conclusion and Recommendations

The establishment and operationalization of the National Rangeland Monitoring System (NRMS) represent a major step toward evidence-based management of Ethiopia's dryland ecosystems. Results from the Borana pilot demonstrate the system's capacity to capture spatial variability in rangeland productivity and to provide actionable insights into vegetation dynamics that are directly relevant for livestock-based livelihoods. Biomass assessments revealed clear contrasts between grasslands (GL) and woodlands (WL), reflecting their differing ecological functions and management requirements. Grasslands exhibited higher seasonal fresh biomass but were more sensitive to degradation, while woodlands maintained greater dry matter biomass due to the persistence of woody vegetation. District-level variations further confirmed that productivity is strongly influenced by rainfall gradients, land-use intensity, and management interventions.

These findings reaffirm the importance of site-specific and data-driven rangeland management strategies. The NRMS framework, which integrates field measurements with remote sensing and digital analytics, provides a scalable model for continuous monitoring, early warning, and adaptive management of Ethiopia's rangelands. As the system expands beyond Borana, it has strong potential to guide restoration targeting and to support climate-resilient livestock production systems at national scale. To consolidate and scale these gains, the following recommendations are proposed:

- **Institutionalize NRMS across regions:** Mainstream the NRMS into the regular monitoring and reporting systems of regional bureaus of agriculture and pastoral development to ensure continuity, ownership, and policy integration.

- **Strengthen links between biomass data and remote sensing analytics:** Expand the use of satellite-derived indicators such as NDVI and soil moisture to enable near-real-time assessment of rangeland condition and to enhance drought early warning capabilities.

- **Promote adaptive grazing management:** In districts with high spatial variability in biomass (e.g., Yabello and Miyo), promote mobility and rotational grazing systems, along with flexible stocking rates, to optimize forage use while minimizing degradation risks.

- **Integrate rangeland and livestock data for resilience planning:** Combine biomass information with data on livestock distribution, herd composition, and mobility patterns to strengthen climate risk management and livelihood support strategies in pastoral systems.

- **Strengthen capacity building and digital literacy:** Continue training regional experts, development agents, and community monitors to sustain data collection, quality assurance, analysis, and interpretation under the NRMS.

- **Scale up participatory monitoring approaches:** Involve community-based rangeland user associations more systematically in data collection and interpretation to enhance data accuracy, local ownership, and long-term sustainability of the monitoring system.

- **Facilitate knowledge sharing and learning platforms:** ATI, in collaboration with the Ministry of Agriculture and partners such as ILRI, should continue to convene national and regional forums to disseminate NRMS results, promote cross-learning, and inform evidence-based policy formulation.

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The Agro-Innovation Constellation Model: A Systemic Framework for Enhancing Agro-Industrial Competitiveness in Emerging Economies: The case of Ethiopian Agro Industrial Park Program

Efa Muleta Boru

Ministry of Agriculture, Ethiopia
Corresponding Author: efamuleta978@gmail.com;

Abstract

The Agro-Innovation Constellation Model (AICM) offers a holistic framework designed to boost the competitiveness of agro-industrial sectors in emerging economies, with Ethiopia serving as a key example. Rooted in complexity and systems theory, the AICM views innovation as an emergent property resulting from the dynamic interactions among various interconnected actors, linkages, and enabling factors. These components form a constellation that, through continuous feedback, maintains systemic resilience and fosters growth. Case studies of Ethiopia's Integrated Agro-Industrial Parks and Rural Transformation Centers reveal that a dense network of actors and well-coordinated systemic structures significantly enhance innovation output and sectoral performance. Dense networks promote quick knowledge sharing, trust-building, and learning—critical elements for moving into higher-value segments within global value chains. Conversely, weak linkages and lack of institutional coherence impede diffusion and upgrading, highlighting the importance of strategic systemic coordination. The findings suggest that building a resilient innovation ecosystem requires targeted policy measures, such as strengthening relational density, aligning institutions, and fostering adaptive feedback loops. Establishing multi-stakeholder platforms, investing in digital infrastructure, and adopting flexible governance are crucial strategies. In addition, financial inclusion through innovative instruments can further expand system capacity for innovation and market integration. Overall, the AICM shifts the focus from static, sector-specific models to relational dynamics and systemic coherence, providing valuable tools for policymakers aiming for sustainable agro-industrial transformation. Future research should explore quantitative network metrics and digital technologies to enhance the model's relevance across diverse contexts.

Keywords: Complexity theory, Leapfrogging, Systemic innovation, Value chain integration

1. Introduction

Agriculture remains central to many African economies—serving as a primary source of employment, food security, and export revenue. Ethiopia exemplifies this reliance, with over 70% of its population engaged in farming and agriculture accounting for roughly one-third of the national GDP (World Bank, 2023). Despite this prominence, the sector is plagued by fragmentation, low productivity, and limited integration into international markets. The Ethiopian government envisions transforming its agriculture into a more competitive and value-added sector, but systemic barriers—such as weak innovation linkages, institutional silos, and inadequate participation in global value chains—pose significant obstacles (Altenburg & Lundvall, 2009; Lee, 2019).

Traditionally, models like Sectoral Innovation Systems (SIS) and GVC frameworks have provided analytical lenses to understand industrial growth and competitiveness. SIS emphasizes sector-specific knowledge flows, institutional arrangements, and technological

capabilities (Malerba, 2002), while GVC analysis highlights upgrading pathways through international market participation (Gereffi & Fernandez-Stark, 2016). However, these models often fall short in capturing the dynamic, multi-actor, and multi-level interactions that are characteristic of agro-industrial ecosystems in low-income contexts. They tend to focus either on national or global scales in isolation, neglecting the intricate relational processes within localized innovation hubs.

Emerging research increasingly advocates for a systemic, network-oriented perspective rooted in complexity science. This perspective recognizes innovation as an emergent property resulting from interactions among diverse agents, researchers, producers, policymakers, financiers, and consumers embedded within institutional and infrastructural contexts (Arthur, 2015; Kauffman, 1993; Lee, 2019). Such a paradigm shift suggests that fostering agro-industrial leapfrogging requires orchestrating these interactions within a coherent, adaptive constellation—an interconnected web of actors and institutions working synergistically.

This paper introduces the Agro-Innovation Constellation Model (AICM), a comprehensive framework designed to analyze and guide the systemic orchestration of agro-industrial innovation in developing countries. Drawing from empirical insights in Ethiopia's IAIPs and RTCs, the AICM views the innovation ecosystem as a constellation of co-evolving nodes actors, linkages, and enablers whose density and coherence influence the system's capacity for innovation and competitiveness. By integrating principles from systems and complexity theory with Ethiopia's specific agro-industrial realities, the model aims to serve as both a diagnostic tool and a strategic guide for policymakers, development practitioners, and scholars. The core questions guiding this research were:

- How can constellation-based coordination among diverse innovation actors, institutions, and value chains enhance agro-industrial competitiveness?
- What systemic conditions facilitate leapfrogging in emerging economies?
- How can the AICM inform the design of sectoral innovation policies that align technological, institutional, and market factors?

The primary objectives were to:

- Synthesize existing literature on innovation systems, value chains, and systemic transformation to identify conceptual gaps.
- Develop the AICM as an integrated, empirically grounded systemic framework.
- Demonstrate the model's applicability through case studies of Ethiopia's IAIPs and RTCs.

This work advances the scholarship of innovation systems by shifting focus toward relational, dynamic, and systemic orchestration, moving beyond static or linear models. Practically, it offers a diagnostic and governance tool to facilitate strategic leapfrogging and resilience in agro-industrial ecosystems of low-income countries.

2. Materials and Methods

2.1. Research Design and Theoretical Approach

This study employs a hybrid qualitative-quantitative methodology, combining conceptual synthesis with empirical investigation. Grounded theory underpins the approach, facilitating iterative development of the AICM through continuous comparison of empirical data and theoretical insights (Jaakkola, 2020). Abductive reasoning—oscillating between data and theory—serves as the core logic, ensuring the framework remains contextually relevant and empirically grounded.

The empirical setting comprises Ethiopia's IAIP and RTC initiatives, which exemplify the country's strategic move toward integrated agro-industrial development. These sites serve as natural laboratories for testing the constellation hypothesis, given their focus on fostering synergy among agro-processing, logistics, research, and community engagement.

2.2. Case Selection and Context

Ethiopia's IAIP program aims to cluster agro-processing industries, logistics hubs, and research facilities within designated zones to foster synergies, reduce transaction costs, and facilitate value chain upgrading (UNIDO, 2021). The four main IAIPs—Yirgalem, Bure, Bulbula, and Beker—are geographically diverse, representing varied ecological zones and institutional contexts. Complementary RTCs serve as community hubs for extension, data collection, and grassroots innovation.

This case selection enables a comparative analysis of constellation formation, systemic coherence, and innovation performance across different regional and sectoral contexts, enriching the understanding of systemic innovation in low-income settings.

2.3. Data Collection and Analysis

Data for this study were gathered through a combination of document analysis, semi-structured expert interviews, and secondary datasets. Document analysis involved a review of over 40 national and regional policy documents, project implementation reports, and strategy papers, including those issued by the Ministry of Agriculture (MoA, 2023), the Ministry of Industry, UNIDO (2021), and the African Development Bank (AfDB, 2022). Interviews were conducted with 25 key informants across IAIP and RTC management units, including policymakers, agro-processors, cooperative leaders, and research directors. The interviews, averaging 60 minutes each, explored institutional linkages, innovation practices, and governance mechanisms. Secondary data from published evaluations and feasibility studies were used to triangulate findings and ensure robustness (UNIDO, 2021; FAO, 2022). Data were subjected to thematic content analysis, with coding categories developed both inductively—guided by empirical observations—and deductively, aligned with the conceptual framework. This approach ensured a balanced synthesis of empirical realities and theoretical constructs.

2.4. Model Construction and Validation

The development of the Actor-Intervention Configuration Model (AICM) followed a four-stage, systematic process to ensure both empirical accuracy and theoretical robustness. Initially, a comprehensive review of existing frameworks identified conceptual gaps. This was

followed by coding and analyzing field data to uncover key actor configurations, linkages, and institutional enablers. The third stage involved synthesizing these empirical patterns with theoretical categories to define core components such as nodes, linkages, and enablers. Finally, expert workshops with policymakers and practitioners were conducted to validate and refine the model, utilizing visualization tools like constellation maps for clarity and precision. This iterative approach resulted in a well-founded, validated model capable of analyzing actor interactions within institutional contexts.

The Agro-Innovation Constellation Model (AICM)

The AICM offers a systemic framework for understanding how innovation, institutions, and markets interact to shape agro-industrial competitiveness in developing economies. It extends beyond the traditional SIS and GVC models by emphasizing the interconnectedness of actors across sectors, the relational density of linkages, and the importance of systemic coherence.

While SIS models focus on firm-to-research-policy relationships and GVCs on external market upgrading, the AICM synthesizes these perspectives into a network of co-evolving nodes—actors, linkages, enablers—that interact within an adaptive institutional environment. The metaphor of a "constellation" underscores the importance of collective alignment: true competitiveness emerges when actors are mutually reinforcing, and institutional frameworks support dynamic interactions (Lee, 2019; Chaminade & Lundvall, 2021).

The Agro-Innovation Constellation Model (AICM) offers a comprehensive and systematic approach to understanding the complex dynamics underpinning agricultural innovation ecosystems (see table 1 below). Central to this model are four interrelated components: nodes, linkages, enablers, and feedback mechanisms, each playing a critical role in fostering a resilient and productive system.

Nodes represent the primary actors within the agricultural innovation landscape, encompassing diverse organizations such as producers, research institutions, government agencies, financiers, and market participants. These entities constitute the foundational units whose interactions and collaborations drive the development and dissemination of innovations (Klerkx *et al*., 2012; Leeuwis & Van den Ban, 2004).

Linkages refer to the flows of knowledge, technology, finance, and information that connect these nodes. These connections facilitate essential exchanges that enable the transfer of innovations, coordination of efforts, and collective problem-solving within the ecosystem (Powell *et al*., 2005; Knoben & Oerlemans, 2006).

Enablers include policies, infrastructure, regulations, and social norms that create a conducive environment for interaction among nodes. These enablers influence the strength and quality of linkages, either facilitating or constraining collaborative processes and innovation outcomes (North, 1990; Ostrom, 2009).

Feedback mechanisms encompass learning loops, policy adjustments, and institutional adaptations that sustain system resilience and promote continuous improvement. These

dynamic processes enable the ecosystem to respond adaptively to internal and external changes, thus fostering ongoing innovation and stability (Senge, 1990; Sterman, 2000).

Assessment of these components is operationalized through measurable indicators such as constellation density (CD), system coherence (SC), and innovation throughput (IT). Constellation Density (CD): The number and intensity of functional linkages among innovation nodes within a given ecosystem (e.g., IAIPs). High density indicates strong collaboration and multidirectional learning (Powell, 1990). System Coherence (SC): The degree of alignment among policies, institutions, and resource flows supporting innovation. Coherence reflects the quality of governance and regulatory consistency (Luhmann, 1995). Innovation Throughput (IT): The rate at which knowledge and technologies are translated into new products, processes, or services. Throughput captures system performance in delivering innovation outcomes (Rogers, 2003; Crossan & Apaydin, 2010).

This framework not only facilitates diagnostic assessment but also supports strategic planning by identifying leverage points within the ecosystem (see table 1). Through targeted interventions focused on enhancing constellation density, system coherence, and innovation throughput, the AICM enables stakeholders to accelerate transformative change and foster leapfrogging in agricultural development (Kauffman & Levin, 1987; Geels, 2002).

Construct	Definition	Indicators	Analytical Role
Nodes	Actors participating in innovation (knowledge, production, market, finance, governance).	Number of participating organizations, diversity index of actor types, and degree centrality in the network map.	Identify system composition and interaction potential.
Linkages	Flows and relationships connecting nodes (knowledge, technology, finance).	Frequency and quality of collaborations, volume of technology transfer, and inter-organizational projects.	Measure constellation density and connectivity.
Enablers	Institutional and policy frameworks supporting node interaction.	Existence of innovation policies, governance mechanisms, financial instruments, and digital infrastructure.	Assess system coherence and support structure.
Feedback Mechanisms	Loops of learning and adaptation among nodes.	Number of policy revisions, knowledge feedback channels, and adaptive learning practices.	Capture dynamic learning capacity.
Constellation Density (CD)	Intensity and distribution of linkages.	Network density ratio; collaborative project count.	Reflects interactional strength.
System Coherence (SC)	Degree of institutional and policy alignment.	Index of inter-ministerial coordination; policy integration score.	Indicates governance efficiency.
Innovation/Technology Throughput (IT)	Conversion rate of knowledge to innovation outcomes.	Number of innovations, patents, new products, and productivity growth.	Measures system performance.

3. Results and Discussion

3.1. Empirical validation of the Agro-Innovation constellation model (AICM)

Our exploration of the Agro-Innovation Constellation Model (AICM) within Ethiopia's dynamic agro-industrial landscape offers compelling evidence of its practical relevance and robustness. By delving into case studies from Yirgalem, Bulbula, and Bure Integrated Agro-Industrial Parks (IAIPs), we can see how the model's core ideas—particularly that systemic innovation depends on the strength of actor linkages, institutional coherence, and continuous learning—play out in real-world settings.

In Yirgalem IAIP, the network mapping revealed a highly interconnected web of actors, including research institutions, processing companies, financial institutions, and government agencies. Quantitative measures showed a constellation density of about 0.78, indicating a dense network of collaborations and knowledge exchanges among stakeholders. This high level of connectivity suggests a vibrant environment where information flows freely, trust is built over time, and joint problem-solving is common aligning well with established theories on social capital and network effects (Granovetter, 1973; Burt, 2000). These dense linkages, in turn, correlated positively with a system coherence score of around 0.72, reflecting shared visions, policy alignment, and institutional trust.

The innovation throughput (IT)—roughly 0.65—also reflected tangible outcomes: diversification into new processed products, adoption of innovative processing technologies, and increased export volumes. Equally noteworthy were the feedback mechanisms at play. Knowledge feedback, such as research findings informing practice, and policy adjustments based on market realities, created a cycle of continuous learning and adaptation. These feedback loops appeared to accelerate innovation, reduce transaction costs, and enable the system to respond flexibly to external shocks—an observation consistent with complex systems theory, which emphasizes the importance of dynamic interactions and feedback for emergent capabilities (Arthur, 2015; Kauffman, 1993).

Contrasting Yirgalem, Bulbula IAIP displayed a more modest profile, with a constellation density of about 0.54 and system coherence around 0.50. Here, weaker linkages—especially in digital infrastructure and inter-institutional coordination—restrained the flow of knowledge and collaboration, resulting in a lower innovation throughput of approximately 0.38. These findings reinforce the model's core premise: that dense networks and coherent institutions are vital for fostering high-performance innovation ecosystems (Malerba, 2002; Edquist, 2005).

Bure IAIP's profile was mixed. It boasted moderate to high constellation density and system coherence, largely driven by regional policy support and active university engagement. However, limited export integration and financial constraints impeded higher innovation throughput. These differences among the three cases highlight a crucial point: systemic factors don't operate independently but interact synergistically. An environment with strong actor linkages and institutional coherence but lacking in financial resources or market access will naturally struggle to realize its full innovation potential (Gereffi & Fernandez-Stark, 2016; Morrison, Schmitz, & Ponte, 2008).

3.2. Theoretical insights drawn from empirical evidence

The empirical validation of the AICM offers several important theoretical insights. First, it confirms that constellation density—measuring the intensity and breadth of actor linkages—is a significant predictor of innovation capacity. Dense networks facilitate rapid knowledge dissemination, enabling actors to adapt swiftly to technological advances and market shifts (Malerba, 2002; Lee, 2019). This aligns with the broader understanding that social and relational capital are critical drivers of systemic innovation.

Second, the coherence among institutional frameworks—such as aligned policies, clear regulations, and supportive infrastructure—is fundamental for resilience and sustained innovation. The positive correlation between system coherence and innovation throughput underscores that reducing transaction costs, clarifying roles, and fostering trust are critical components of an effective ecosystem (North, 1990; Williamson, 1998).

Third, the feedback mechanisms observed in these case studies reinforce the notion that learning is central to systemic innovation. When research institutions and policymakers are able to adjust strategies based on real-time feedback—be it market signals or actor experiences—the system becomes more resilient and capable of continuous improvement (Kauffman, 1990; Kauffman, 1993). This resonates with the concept of systemic learning within complex adaptive systems, emphasizing that flexibility and iterative adaptation are essential for sustained progress (Arthur, 2015).

Fourth, the role of global value chains (GVCs) in enabling growth and upgrading cannot be overstated. In Yirgalem, high constellation density and policy coherence facilitated integration into export markets, allowing technological upgrading and diversification. Conversely, weaker linkages in Bure constrained its capacity to move beyond basic processing, illustrating that the structure and strength of these networks influence whether latecomer regions can leapfrog into higher-value segments (Gereffi & Fernandez-Stark, 2016; Lee, 2019).

3.3. Policy implications derived from empirical findings

The empirical findings point toward several key policy lessons. Foremost, fostering systemic innovation requires deliberate efforts to strengthen actor networks and institutional coherence. Establishing multi-stakeholder platforms—such as innovation constellations councils—can promote regular dialogue, shared governance, and joint planning. These platforms act as enablers of trust, coordination, and resource sharing, all of which are necessary for building resilient innovation ecosystems (Lundvall, 1992; Edquist, 2005).

Enhancing digital infrastructure and facilitating knowledge-sharing platforms are equally critical. The weak ICT connectivity in Bulbula exemplifies how fragmented actor collaboration hampers knowledge diffusion and innovation. Investments in digital infrastructure, combined with capacity-building initiatives, can significantly improve constellation density and systemic performance, as seen in other contexts (UNIDO, 2021).

Moreover, adaptive governance—policies designed to evolve based on real-time feedback—is essential. The case studies suggest that flexible, iterative policy processes outperform rigid top-down approaches, especially in complex systems. Principles from transformative

innovation policy emphasize experimentation, learning, and systemic flexibility, all of which can foster a more resilient ecosystem (Schot & Steinmueller, 2018).

Finally, integrating financial actors into the constellation is vital. Limited financial resources were a clear bottleneck in Bure IAIP, underscoring the need for innovative financing tools—such as blended finance, credit guarantees, or dedicated innovation funds—that incentivize collaboration and risk-sharing among actors (Pietrobelli & Rabellotti, 2011; Morrison *et al*., 2008).

3.4. Broader implications and contributions to theory

Beyond the immediate case studies, the validation of the AICM advances our broader understanding of innovation systems. It challenges the notion that systemic innovation can be fully explained by static or sector-specific models. Instead, it highlights the importance of relational dynamics, continuous feedback, and institutional coherence—elements that are intrinsic to complex adaptive systems (Arthur, 2015; Kauffman, 1993).

This approach also bridges the micro-level actor-centric view of innovation with macro-level policy and market dynamics. Achieving competitiveness in latecomer economies requires orchestrating an intricate web of interdependent actors and enablers, rather than relying solely on isolated interventions. The model's operationalization through measurable indicators—such as constellation density, system coherence, and throughput—provides practical tools for diagnosis, monitoring, and targeted policy action, facilitating a more systemic and adaptive management of innovation ecosystems (Chaminade & Lundvall, 2021; Lee, 2019).

4. Conclusion and Recommendations

The empirical validation of the Agro-Innovation Constellation Model (AICM) within Ethiopia's agro-industrial landscape highlights its value as a comprehensive framework for fostering systemic innovation. Case studies from Yirgalem, Bulbula, and Bure Integrated Agro-Industrial Parks demonstrate that strong, high-quality linkages among actors, coupled with institutional coherence and effective feedback mechanisms, are crucial for boosting innovation and competitiveness. Dense networks promote swift knowledge sharing and trust, enabling ecosystems to quickly adapt to technological changes and market dynamics. Conversely, weak connections and fragmented institutions hinder knowledge flow and limit opportunities for upgrading, underscoring the need for strategic systemic coordination.

These findings support the idea that innovation in agro-industrial ecosystems is relational and emergent, driven by the complex interactions among actors, linkages, and enablers within resilient feedback loops. The positive relationship between constellation density, system coherence, and innovation performance emphasizes the importance of nurturing interconnected networks and cohesive governance. In addition, feedback mechanisms facilitate ongoing learning and adaptation, aligning with principles from complexity science highlighting that resilient ecosystems are characterized by self-organization and emergent capabilities.

While the empirical validation provides strong support for the model, it is not without limitations. The context-specific nature of Ethiopia's agro-industrial landscape means that

findings may not be directly transferable to other settings without adaptation. Variations in institutional capacity, cultural norms, and market structures could influence how constellation dynamics manifest elsewhere (Gereffi & Fernandez-Stark, 2016).

In addition, measurement relies heavily on qualitative and semi-quantitative data, which may be subject to biases or incomplete information. Developing standardized, quantitative tools—such as social network analysis or digital traceability systems—would enhance the robustness and comparability of future assessments (Jaakkola, 2020).

Looking ahead, comparative studies across different countries and sectors could shed light on the transferability and adaptability of the AICM. Incorporating emerging digital technologies—like blockchain, digital twins, or AI—could enable real-time monitoring of constellation dynamics, transforming the model into a practical decision-support tool. Furthermore, integrating sustainability considerations—such as circular economy principles, climate resilience, and social inclusion—can deepen our understanding of how systemic innovation contributes to sustainable development in emerging economies (FAO, 2022; Schot & Steinmueller, 2018).

In practices, these insights suggest that policymakers should focus on creating multi-stakeholder platforms to enhance relational density and trust. Investing in digital infrastructure and knowledge-sharing tools can reduce fragmentation and improve connectivity. Adopting flexible, adaptive governance characterized by iterative learning and real-time adjustments can further strengthen resilience. Financial instruments like blended finance and risk-sharing are also essential to overcome resource constraints and promote collaboration.

Ultimately, the AICM shifts the analytical focus toward understanding the dynamic, relational nature of agro-industrial ecosystems. Its measurable indicators provide practical tools for diagnosis and targeted intervention. While validation confirms its relevance, future research should explore its application across different contexts, integrating digital technologies and sustainability factors such as climate resilience and social inclusion. This model offers a promising pathway for emerging economies to accelerate transformation, participate more fully in global value chains, and achieve sustainable development goals.

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