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COLLEGE OF AGRICULTURE AND NATURAL RESOURCES

Research Report

On

Mapping Trends, Dynamics, and Challenges of Small-Scale Irrigation Technology in East Gojjam Zone, Ethiopia

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List of the abbreviations and acronyms

ADLI – Agricultural Development-Led Industrialization

AUC – Area Under the Curve

BCR – Benefit-Cost Ratio

CI – Confidence Interval

CSA – Central Statistical Agency

ETB – Ethiopian Birr

FAO – Food and Agriculture Organization

FGDs – Focus Group Discussions

GDP – Gross Domestic Product

GTP – Growth and Transformation Plans

IFAD – International Fund for Agricultural Development

KAM – Knowledge Assessment Methodology

MoA – Ministry of Agriculture

NPV – Net Present Value

OR – Odds Ratio

UNICEF – United Nations Children's Fund

VIF – Variance Inflation Factor

WB – World Bank

Abstract

Small-scale irrigation (SSI) technologies offer a promising solution to address challenges of low agricultural productivity, unreliable rainfall, and rural poverty in Ethiopia. However, their performance and sustainability remain inconsistent, particularly in regions like East Gojjam Zone, Amhara Region. This study aimed to assess the adoption trends, performance challenges, and economic viability of furrow irrigation and motor pump systems across two districts—Debre Elias and Machakel. A cross-sectional, mixed-methods design was employed, drawing on data from 280 smallholder farmers selected through a multistage sampling procedure. Descriptive analysis showed moderate irrigation access, but a 25.4% overall defect rate raised concerns about technology reliability. Binary logistic regression identified income, credit access, and training as key factors reducing defect occurrence, while motor pump use and larger irrigated areas increased risk. Economic analysis revealed that furrow systems were more profitable, yielding a higher five-year Net Present Value and Benefit-Cost Ratio than motor pumps. Despite these gains, sustainability challenges persisted, including soil degradation and inefficient water use. The study also found notable district-level variation, with furrow systems dominating in Debre Elias due to affordability, and topography favoring gravity flow and motor pumps preferred in Machakel for their productivity potential. Qualitative findings highlighted high maintenance costs and limited institutional support as barriers to sustained use. Based on these insights, the study recommends strengthening farmer access to credit, improving training services, and upgrading irrigation technologies to enhance the long-term impact of SSI on smallholder livelihoods and agricultural sustainability.

Keywords: Small-scale irrigation, technology utilization, sustainability, economic viability, East Gojjam Zone, Ethiopia

1. Introduction

Agriculture plays a central role in Ethiopia's economy, contributing nearly 47% to the national gross domestic product (GDP), accounting for 90% of exports, and providing employment for close to 70% of the population (CSA, 2018; World Bank, 2022). As the dominant livelihood source for rural households, the performance of this sector directly influences food security, rural incomes, and national development. However, the country's agricultural productivity is heavily constrained by its dependence on rain-fed farming, which is increasingly unreliable due to climatic variability. Irregular and poorly distributed rainfall patterns, combined with frequent drought events, continue to undermine crop yields and expose smallholder farmers to food insecurity, land degradation, and poverty (UNICEF, 2021).

In light of these challenges, the promotion of irrigated agriculture has become a critical component of Ethiopia's development strategy. By enabling consistent water availability, irrigation helps to stabilize production, reduce vulnerability to drought, and improve the resilience of farming communities. It also supports more efficient use of land and labor while fostering a transition toward commercial, market-oriented agriculture (Awulachew et al., 2010; World Bank, 2006). Recognizing these benefits, the Ethiopian government and its development partners have made irrigation development a national priority, integrating it into major policy frameworks such as the Growth and Transformation Plans (GTP I & II) and the Agricultural Development-Led Industrialization (ADLI) strategy (MoA, 2014).

Among various irrigation modalities, small-scale irrigation (SSI) systems—typically managed by individuals or communities and covering areas under 200 hectares—have gained traction due to their relative affordability, adaptability, and decentralization (MoWR, 2011). These systems have been actively promoted as tools for achieving food self-sufficiency, income diversification, and improved rural livelihoods. In addition to facilitating year-round cultivation, SSI offers opportunities for increasing land productivity, reducing risk exposure, and enhancing household nutrition and income (FAO, 2018; MoA, 2020).

Despite these potential advantages, the development and performance of SSI in Ethiopia remain far below expectations. Although the country's total irrigation potential is estimated to exceed 5.3 million hectares, only a small fraction has been effectively utilized (MoWR, 2011). Key constraints include limited access to affordable irrigation technologies, low levels of technical knowledge among farmers, high upfront investment costs, and weak extension and institutional support (Burney & Naylor, 2012; Kaleb et al., 2014). Furthermore, challenges such as inefficient water use, soil degradation, and lack of maintenance undermine the sustainability of existing systems. These systemic issues call for renewed efforts to identify region-specific barriers and opportunities for improving SSI implementation and outcomes.

Empirical studies across diverse agro-ecological contexts have produced mixed evidence regarding the effectiveness of SSI in improving agricultural performance and household well-being. While some research points to clear benefits in terms of productivity and income gains, others emphasize that outcomes depend heavily on context-specific factors such as land size, access to markets, institutional support, and farmers' capacity to manage irrigation technologies (Doss, 2001; Quisumbing & Pandolfelli, 2010; Namara et al., 2010). However, most existing literature overlooks micro-level analyses of sustainability challenges, particularly in high-potential zones like the East Gojjam Zone of the Amhara Region.

In this region, smallholder farmers have increasingly adopted furrow and motor pump irrigation systems to supplement rainfall and stabilize crop production. Yet, sustainability concerns persist. High defect rates, limited technical support, and socioeconomic inequalities continue to constrain effective utilization. For example, while furrow systems are widely used due to their low cost, motor pumps—though more flexible—exhibit higher breakdown rates, particularly among farmers with limited incomes or technical skills.

To address these critical gaps, the present study investigates the adoption patterns, sustainability dynamics, and performance outcomes of small-scale irrigation systems in two districts of East Gojjam Zone: Debre Elias and Machakel. Drawing on both quantitative and qualitative data from a 2024/25 survey of 280 smallholder farmers, the research explores how technological attributes, farmer characteristics, and institutional factors interact to shape the effective use and longevity of SSI technologies. Particular attention is paid to the comparative performance of furrow and motor pump systems under varying socioeconomic and environmental conditions.

The study is conceptually grounded in Rogers' (2003) Diffusion of Innovations theory, which explains how factors such as perceived complexity, relative advantage, and adopter profiles influence technology uptake. Complementing this, Postel's (1999) sustainability framework on water resource management is employed to assess environmental trade-offs. In critiquing Ethiopia's prevailing linear and top-down innovation dissemination approach (Mikinay, 2013), the study emphasizes the need for context-specific, demand-responsive models that reflect farmers' realities and agroecological diversity (Dhillon & Moncur, 2023).

Ultimately, the study provides empirical evidence to inform regionally tailored policy interventions that strengthen the sustainability and resilience of smallholder irrigation systems. Its findings offer actionable insights for development practitioners, policymakers, and local stakeholders aiming to improve irrigation governance, enhance rural livelihoods, and advance Ethiopia's broader agenda of sustainable agricultural transformation.

1.2 Statement of the Problem

Small-scale irrigation (SSI) has long been recognized as a strategic tool for boosting agricultural productivity and enhancing the resilience of smallholder farmers in Ethiopia—particularly in the face of erratic rainfall and climate variability. The Amhara Region, and East Gojjam Zone specifically, presents favorable agroecological conditions conducive to SSI development. Yet, despite this potential, the actual utilization of irrigation resources remains limited and uneven, constrained by a complex mix of technical, economic, institutional, and environmental challenges.

SSI technologies such as furrow irrigation and motor pumps are widely promoted and increasingly adopted in East Gojjam. However, their long-term performance and sustainability remain in question due to frequent system defects, limited technical support, and inadequate maintenance capacity. These challenges are exacerbated by high operational costs and insufficient access to quality training, undermining the overall efficiency and reliability of irrigation interventions (Namara et al., 2010).

Economic viability is further challenged by disparities in household income and restricted access to credit services, which inhibit investment in irrigation technologies and infrastructure (Burney & Naylor, 2012). Moreover, gender inequities and low levels of farmer education continue to impede inclusive participation and informed use of irrigation tools—barriers consistently identified across the literature on agricultural innovation in sub-Saharan Africa (Doss, 2001; Quisumbing & Pandolfelli, 2010).

In addition to individual-level constraints, institutional weaknesses present systemic obstacles. Poor coordination between research, extension, and implementation agencies—including underperforming platforms such as the Agricultural Development Partners Linkage Advisory Council (ADPLAC)—limit the reach and impact of SSI programs (Kaleb et al., 2014). These institutional gaps reduce farmers' access to technical advice, hinder innovation diffusion, and constrain adaptive support services.

Environmental concerns further complicate the effective use of SSI. Inadequate water management practices and insufficient awareness of soil conservation measures contribute to degradation risks and suboptimal resource use, making sustainability trade-offs poorly understood and rarely addressed in existing schemes (FAO, 2017).

Despite considerable investment and policy attention, Ethiopia has yet to fully realize its irrigation potential—estimated at over 5.3 million hectares (MoWR, 2011). Continued reliance on fragmented support systems, coupled with low levels of technical literacy and innovation uptake, continues to limit progress toward sustainable irrigation expansion.

Although several studies have examined the general benefits of SSI, there remains a lack of location-specific evidence that captures the nuanced interplay of socio-economic status, irrigation technology types, and institutional support systems. In East Gojjam Zone, empirical analysis on adoption effectiveness, operational challenges, and sustainability trade-offs is particularly scarce.

This study, therefore, seeks to fill that knowledge gap by systematically examining the technological, socioeconomic, and institutional factors that influence the utilization, functionality, and sustainability of small-scale irrigation systems in Debre Elias and Machakel districts. By identifying key barriers, drivers, and trade-offs within existing irrigation practices, the study aims to generate actionable insights to inform locally responsive policies and development strategies that strengthen smallholder resilience, improve system performance, and advance sustainable agricultural transformation in Ethiopia.

1.3 Objectives

1.3.1 General Objectives

To conduct a comprehensive analysis of mapping trends, sustainability dynamics, and future trajectories of small-scale farming technology within the East Gojjam Zone, Ethiopia.

1.3.2 Specific Objectives

Theme I

1. To examine and categorize the diverse range of small-scale farming technologies accessible within the region, focusing on their types, functionalities, and availability across different agricultural settings.

2. Evaluate the factors contributing to the (in)effective implementation of farming technologies in small-scale agricultural practices, focusing on technological suitability, farmer training, and institutional support, and further examine key drivers of successful technology adoption and utilization.

Theme II

1) Conduct a comprehensive analysis to identify and examine the sustainability challenges arising from the adoption and utilization of small-scale farming technology, with a focus on soil degradation, water resource management, and biodiversity conservation.

2) Evaluate the economic sustainability challenges inherent in the adoption and utilization of small-scale farming technology, focusing on financial viability, resource accessibility, and market dynamics affecting the livelihoods of smallholder farmers.

The major research questions of this study are.

- What are the various types and classifications of small-scale farming technologies available within the East Gojjam Zone?
- What factors influence the successful and unsuccessful deployment of farming technologies in small-scale agricultural operations?
- What specific sustainability challenges are associated with the adoption and utilization of small-scale farming technology, and how do they impact agricultural practices within the area?

1.5 Significance of the Study

The significance of the study for the outlined objectives lies in its potential to address critical issues and contribute to the advancement of agricultural practices in the East Gojjam Zone, Ethiopia. Specifically:

Informing Policy and Decision-Making: By identifying and categorizing the diverse range of small-scale farming technologies accessible within the region, policymakers and stakeholders can make informed decisions regarding resource allocation, technology adoption, and support mechanisms for farmers.

Enhancing Technology Implementation: Understanding the factors contributing to the success or failure of farming technologies in small-scale agricultural practices can inform the development of strategies to enhance implementation processes. This knowledge can lead to more effective training programs, technical support, and resource allocation tailored to the needs of local farmers.

Promoting Sustainable Agriculture: Examining the sustainability challenges inherent in the adoption and utilization of small-scale farming technology provides insights into the environmental, economic, and social dimensions of agricultural practices. Addressing these challenges can promote the adoption of sustainable farming methods, reduce environmental degradation, and improve the resilience of farming communities to climate change and other external pressures.

Empowering Small-Scale Farmers: By addressing the identified challenges and providing solutions, the study can empower small-scale farmers to enhance their productivity, income, and livelihoods. This empowerment can contribute to poverty reduction, food security, and overall socio-economic development within the region.

2. LITERATURE REVIEW

2.1. Definition and Classification of Irrigation Schemes

Irrigation, broadly defined, is the artificial application of water to soil to supplement rainfall and support crop growth (FAO, 1997). While its intensity and frequency may vary, irrigation serves a common purpose: reducing the risks posed by unreliable or insufficient rainfall. Historically, irrigation has underpinned agricultural systems and civilizations for millennia—from ancient Egypt's reliance on the Nile to complex systems developed along the Tigris, Euphrates, Indus, and Yellow Rivers (Schilfgaarde, 1994).

In Ethiopia, irrigation has long complemented rain-fed agriculture, especially in regions like North Shoa, East Gojjam, and Hararghe. While traditional systems have existed for centuries, modern irrigation only gained prominence in the mid-20th century, initially through private commercial farms in the Awash Valley (MoA, 1993).

Irrigation schemes are generally classified by their command area. Large-scale schemes exceed 3,000 hectares and are often publicly or commercially managed. Medium-scale schemes, typically spanning 200–3,000 hectares, are community-based but receive public support. Small-scale irrigation, defined as schemes covering less than 200 hectares, is commonly farmer-led and community-managed (ATA, 2013). A further sub-category, household irrigation, involves plots under 5 hectares and is usually operated by individual families. These smaller systems are particularly important in Ethiopia, where they often respond more directly to local needs and are built on strong farmer engagement (Taffa, 2002).

Small-scale irrigation technologies—motor pumps, furrow systems, drip irrigation, and solar pumps—are pivotal in transforming subsistence agriculture across developing nations, particularly in Sub-Saharan Africa, where 40–70% of rural incomes derive from farming (FAO & WFP, 2012). These tools enable double cropping, increase yields by 20–30%, and reduce labor burdens, particularly for women and children, while supporting domestic water access and income diversification (e.g., equipment rental)

(Namara et al., 2010; FAO, 2017). In Ethiopia, where agriculture accounts for 47% of GDP and employs 85% of the workforce (CSA, 2018), irrigation aligns with national goals of food security and poverty reduction under the ADLI framework (MoA, 2014). Yet, their adoption and sustainability face multifaceted barriers—technological, socioeconomic, environmental, and institutional—underscoring a need for context-specific analysis.

2.2. Small-Scale Irrigation Management

Effective small-scale irrigation depends not only on water availability but also on how it is managed. Byrnes (1992) identifies three core dimensions of irrigation management: water use, control infrastructure, and organizational processes. Water use encompasses the planning and execution of water acquisition, allocation, and distribution. Allocation determines access rights, while distribution ensures water reaches farms in the right amount and at the right time. In regions with excessive moisture, drainage becomes a critical part of system design.

Decision-making in small-scale systems includes activities related to the construction, operation, and maintenance of infrastructure, as well as organizing how water is shared and used. Evidence suggests that transferring management responsibilities to users—often without full scheme ownership—can improve efficiency, equity in water distribution, and overall productivity, while reducing the burden on public institutions (IWMI, 2005).

2.3. Environmental Impact of Small-Scale Irrigation

Small-scale irrigation (SSI) plays a vital role in enhancing agricultural productivity, building resilience to climate shocks, and supporting rural livelihoods. However, it also presents notable environmental risks if not properly managed. In Ethiopia, common challenges include soil salinization, waterlogging, and the depletion of surface and groundwater resources. These risks are often exacerbated by the use of unlined canals, poorly regulated water extraction, and limited downstream flow control, particularly in traditional schemes. Such practices can accelerate watershed degradation and reduce long-term water availability.

The environmental and health implications of SSI in Ethiopia stem not only from technical deficiencies but also from institutional and knowledge-related gaps. Limited awareness of sustainable water use, insufficient capacity to implement environmental safeguards, and underutilization of indigenous practices all contribute to the degradation of ecosystems (FAO, 1997). Moreover, the environmental impacts of irrigation are both on-site and off-site, affecting areas beyond the irrigated plots, including upstream and downstream ecosystems (Wagnew, 2004). These dynamics highlight the urgent need for integrating environmental considerations into irrigation planning, promoting adaptive water governance, and strengthening institutional capacity to manage trade-offs between productivity and sustainability.

2.4. Empirical Evidence on Small-Scale Irrigation

2.4.1 Status and Potential of Small-Scale Irrigation in Ethiopia

Small-scale irrigation (SSI) presents a strategic opportunity to enhance rural livelihoods and climate resilience in Ethiopia. Despite its potential, the sector remains underutilized due to infrastructural gaps, weak water governance, and fragmented institutional coordination. Recent initiatives, particularly those led by the Agricultural Transformation Agency (ATA), focus on expanding household- and community-based irrigation systems. These efforts prioritize low-cost, context-sensitive technologies, participatory planning, and localized ownership, aligning well with Ethiopia's diverse agroecological conditions and decentralized governance.

The Ministry of Irrigation and Lowlands underscores that SSI, primarily led by smallholder farmers, can more rapidly contribute to national development goals compared to large-scale projects. Ethiopia's growing potential for SSI is further supported by substantial investments, including the distribution of 54,515 water pumps in the 2022 fiscal year, in collaboration with federal and regional governments (Ministry of Irrigation and Lowlands, 2023). It remains a pivotal strategy for enhancing rural livelihoods, strengthening climate resilience, and ensuring food security in Ethiopia. Despite its recognized potential, the sector continues to face challenges such as infrastructural deficiencies, weak water governance, and fragmented institutional coordination. Recent government and donor-led initiatives, notably those spearheaded by the Agricultural Transformation Agency (ATA), are actively promoting the expansion of household- and community-based irrigation. These efforts emphasize low-cost, context-sensitive technologies, participatory planning, and localized ownership, aligning well with Ethiopia's diverse agroecological conditions and decentralized governance framework.

Empirical studies underscore the significance of complementary services—particularly credit and agricultural extension—in influencing irrigation adoption and intensity of use. Disparities in financial capital remain a significant constraint. Household-level factors such as income, the proportion of irrigated land, and credit availability have shown strong positive effects on income gains from SSI. Notably, institutional barriers disproportionately limit female-headed households from accessing irrigation resources, exacerbating existing inequalities. Addressing these biases is crucial to ensuring inclusive benefits from irrigation development and achieving broader poverty reduction goals.

Moreover, irrigation is not a standalone solution. Its success depends on the functionality of complementary components across the agricultural system—including input markets, extension services, and infrastructure. While projections suggest that well-managed irrigation could contribute up to ETB 140 billion to Ethiopia's economy and lift as many as six million households into food security, this outcome hinges on overcoming systemic institutional failures. Strengthening coordination, enhancing economic inclusion, and fostering sustainable water governance are thus central to realizing the full potential of SSI in Ethiopia's development trajectory**.**

2.4.1 Technology Adoption and Functionality

Furrow irrigation, a gravity-fed system, is widely adopted in resource-constrained settings due to its low cost (5,000 ETB initial) and simplicity, irrigating small plots (<2 ha) with minimal energy use (Postel, 1999). However, its inefficiencies—water loss and uneven distribution—elevate soil erosion risks, with studies estimating 10–30% runoff in sloping terrains (Pretty et al., 2006). Motor pumps, mechanized and versatile, extract water from diverse sources, boosting productivity in water-scarce areas, yet their high costs (15,000 ETB initial, 4,500 ETB/year maintenance) and defect rates (up to 35% regionally) strain smallholders (Burney & Naylor, 2012; Tiwari et al., 2017). Advanced systems like drip irrigation, offering 90% water efficiency, remain rare in Ethiopia due to cost (20,000–30,000 ETB) and complexity, clashing with smallholder realities (Dhillon & Moncur, 2023). Rogers' (2003) Diffusion of Innovations theory frames these dynamics, highlighting relative advantage (yield gains), compatibility (plot size), and complexity as adoption determinants, with Ethiopia's defect-prone systems (25.4% in this study) signaling implementation gaps.

2.4.2 Socioeconomic and Demographic Drivers

Adoption hinges on farmer characteristics. Higher incomes and credit access mitigate technology failures by funding repairs and quality equipment (Feder et al., 1985), as evidenced by this study's findings (OR = 0.80 for income, OR = 0.52 for credit). Education enhances maintenance skills (OR = 0.56), aligning with Foster and Rosenzweig's (2010) learning-by-doing model, while age (OR = 1.03) and gender disparities (OR = 1.46, p = 0.098) suggest older and female farmers face uptake barriers due to physical or resource constraints (Doss, 2001). Ethiopia's male-dominated farming (85% of landholders) and low literacy rates (49% national average) amplify these inequities (CSA, 2018; Quisumbing & Pandolfelli, 2010). Farm size (OR = 1.52) and irrigated area (OR = 1.73) further increase defect risks, reflecting scale-driven equipment stress (Tiwari et al., 2017).

2.4.3. Institutional and Resource Factors

Institutional support shapes technology longevity. Training (OR = 0.29) and extension services (OR = 0.62) reduce defects by building technical capacity, yet Ethiopia's supply-driven model—via ADPLAC—suffers from weak research-extension linkages, high staff turnover, and limited funding (Kaleb et al., 2014; Anderson & Feder, 2004). Only 50% of East Gojjam farmers access training, and government support (OR = 0.72) remains moderate, echoing Kassahun et al.'s (2008) critique of technology transfer failures. Water distance (OR = 1.28) and irrigation experience (OR = 0.94) highlight resource and skill impacts, with longer distances straining motor pumps and experience mitigating risks (Namara et al., 2010). Ethiopia's Knowledge Assessment Methodology ranking (140/145) underscores systemic innovation deficits (KAM, 2012).

2.4.4 Sustainability Challenges

Sustainability hinges on balancing productivity with environmental and economic viability. Furrow irrigation's water inefficiency risks soil degradation (10–20 t/ha/year erosion rates in Ethiopia's highlands) and biodiversity loss, while motor pumps' energy demands (fuel/electricity) elevate costs and emissions (Postel, 1999; Pretty et al., 2006). Economic analyses show furrow's cost-effectiveness (BCR = 3–4) outpaces motor pumps (BCR = 1–2) over time, yet defect rates (25–35%) erode gains, particularly for low-income farmers (Burney & Naylor, 2012). Globally, sustainable intensification frameworks advocate water-efficient technologies (e.g., drip), but their absence in East Gojjam reflects affordability and infrastructure gaps (Dhillon & Moncur, 2023). Ethiopia-specific studies (e.g., Mikinay, 2013) note linear dissemination overlooks farmer needs, leaving a research void on region-specific sustainability trade-offs—soil health, water management, and livelihoods—addressed herein.

This study synthesizes adoption theory (Rogers, 2003), human capital models (Foster & Rosenzweig, 2010), and sustainability lenses (Postel, 1999), revealing a gap in holistic analyses of East Gojjam's irrigation dynamics. By integrating these perspectives with empirical data (e.g., 25.4% defect rate, NPV disparities), this study advances understanding of technology efficacy and resilience in smallholder systems.

A growing body of empirical research in Ethiopia underscores the positive impact of small-scale irrigation (SSI) on household income, food security, and cropping intensity. Access to irrigation consistently enhances agricultural productivity and reduces households' vulnerability to climate-related shocks. However, these benefits are not uniform across regions; they are influenced by factors such as institutional arrangements, local water governance, and the technical capacity of farmers to operate and maintain irrigation systems. Studies highlight the need for stronger coordination among public agencies, NGOs, and farmer organizations to ensure long-term sustainability and equitable water access.

In addition to performance outcomes, research also sheds light on the drivers and barriers affecting the adoption and effective use of SSI technologies. Socioeconomic factors—

including age, education, household size, and income—play a decisive role in shaping farmers' ability and willingness to invest in irrigation (Asfaw & Mekonen, 2024; Teha, 2021). Access to financial services, particularly credit, emerges as a critical enabler, reducing constraints related to the initial cost of infrastructure and mitigating risks associated with equipment failure and maintenance. These findings suggest that enhancing SSI utilization and uptake requires integrated support—linking technical assistance with institutional and financial inclusion.

Conceptual Framework of the Study

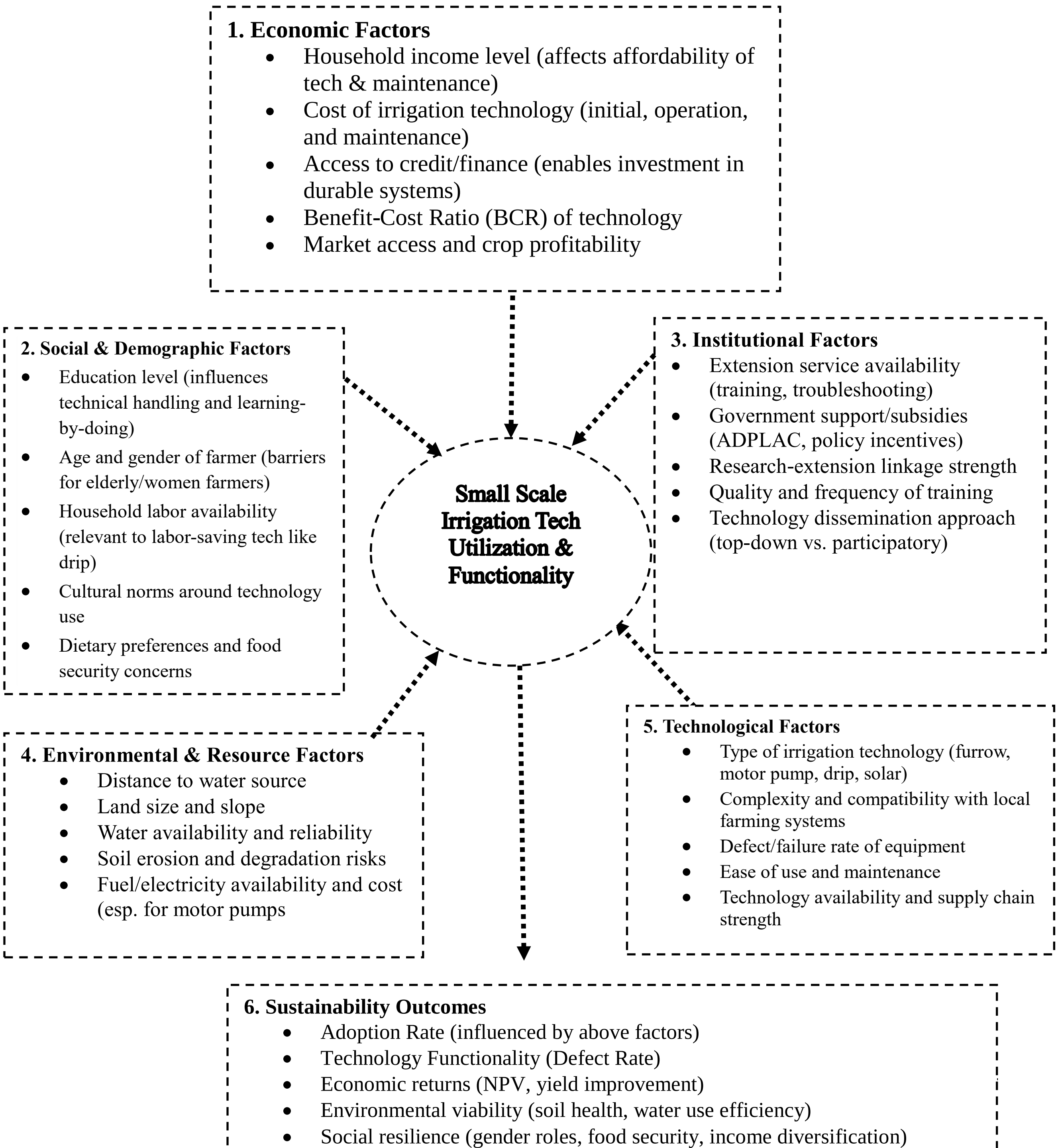

Figure 1: Conceptual Framework of the Study (own developed,2025)

3. RESEARCH METHODOLOGY

3.1 Description of Study Area

East Gojjam Zone, in Ethiopia's Amhara Region (10°20′N, 37°43′E, elevation 2,446 m), spans diverse agroecologies, supporting 2.15 million people—90% rural (CSA, 2007). Renowned for teff and pulse production, it cultivates wheat, barley, maize, and oilseeds on smallholdings (mean = 1.5 ha) (CSA, 2012). Debre Elias and Machakel districts, focal to this study, exemplify irrigation adoption, furrow and motor pump systems irrigating 0.63 ha plots amidst variable topography and water access. This setting, surveyed in 2024/25, reflects Ethiopia's mechanization push (MoA, 2014) and its sustainability challenges, offering a small-scale version of smallholder dynamics.

3.2 Research Design

A mixed-method, cross-sectional design was employed, capturing data from 280 farmers in 2024/25. Quantitative surveys quantified technology prevalence (e.g., 72.5% furrow), defect rates (25.4%), and socioeconomic covariates (e.g., income, credit), while qualitative focus group discussions (FGDs) explored adoption drivers and sustainability perceptions (e.g., soil degradation concerns). This approach triangulates findings (Hosmer et al., 2013), to dissect irrigation technology trends and challenges in East Gojjam Zone.

3.3 Sampling Techniques

Multistage sampling ensured representativeness: (1) Purposive district selection targeted Debre Elias and Machakel for their irrigation prominence; (2) Stratified sampling within kebeles stratified farmers by farm size (<2 ha), technology type (motor pump vs. furrow), and adoption extent; (3) Simple random sampling selected 154 farmers in Debre Elias and 126 in Machakel, proportional to population size. Key informants—extension agents and farmers—augmented insights, reflecting regional diversity and adoption patterns (Yamane, 1967).

3.4 Sample Size and Data Collection

Using Yamane's (1967) formula ($n = N / [1 + N(e^2)]$, $e = 0.05$, using a 5% margin of error, a target population of approximately 1,400 smallholder farmers was estimated. To account for potential non-responses, a 10% buffer was applied, resulting in a required sample size of 311 farmers. Ultimately, 280 complete and valid responses were obtained and used for analysis, aligning with the desired level of precision. This approach aligns with established survey design practices in socioeconomic research (Yamane, 1967; Cochran, 1977), and is commonly used in large-scale household surveys to account for anticipated attrition and incomplete responses (UNICEF, 2012; CSA & World Bank, 2017). For instance, the Ethiopia Socioeconomic Survey (ESS) adjusted sampling weights and targets based on expected non-response rates (CSA & World Bank, 2017), while UNICEF's Multiple Indicator Cluster Surveys explicitly recommend a 5–20% upward adjustment (UNICEF, 2012). Additionally, World Bank research emphasizes the importance of such adjustments to mitigate bias and protect data quality (Reyes, Lu, & Ma, 2016). As such, the final sample of 280 farmers reflects a deliberate methodological strategy to uphold representativeness and precision within the study's 5% margin of error.

3.4.1 Primary Data Collection

Structured questionnaires captured demographic (like age in years), socioeconomic (e.g., income), and technology data (e.g., defect rates), validated via pilot testing. Trained enumerators ensured consistency, with field observations of irrigation systems and FGDs (8–10 farmers per session) probing qualitative nuances. Quality checks—double entry, spot audits—ensured reliability (Sirkin, 2006).

3.4.2 Secondary Data Collection

Data from East Gojjam Zone Agricultural Office reports (2017 E.C.), CSA (2018), and peer-reviewed studies (e.g., Namara et al., 2010) contextualized trends and benchmarks, supplementing primary findings.

3.5 Data Analysis

For the identified objective our method of data analysis were employed corresponding to each objective: thus, by employing a combination of both quantitative and qualitative data analysis methods, our investigation yield comprehensive insights into small-scale farming technology dynamics, implementation factors, and sustainability challenges.

Theme I: Small-Scale Farming Technologies

- Quantitative: Descriptive statistics (means, frequencies) detailed technological prevalence (e.g., 72.5% furrow) and functionality (e.g., 35.1% motor pump defects). Binary logistic regression (Stata 17) modeled defect drivers (e.g., OR = 2.34 for motor pump use), with goodness-of-fit assessed via Hosmer-Lemeshow ($p = 0.55$) and AUC (0.88) (Hosmer et al., 2013).

1. Examination and Categorization of Technologies:

- **Quantitative Analysis**: Utilize descriptive statistics to analyze the frequency and distribution of various small-scale farming technologies identified within the study area. This entails calculating measures such as mean, and standard deviation to understand the central tendency and variability of technology adoption. Additionally, employ inferential statistics, such as chi-square tests to identify significant differences in technology adoption across different demographic or geographic factors.
- **Qualitative Analysis**: **Qualitative**: conduct thematic analysis (NVivo) coded FGD data, identifying adoption factors (e.g., training impact, cost barriers), triangulating quantitative results. Qualitative data gathered from interviews, focus groups, or open-ended survey responses. Utilize coding techniques to identify recurring themes and patterns related to small-scale farming technologies. Through this process, themes may emerge regarding the types of technologies preferred by farmers, perceived benefits, and challenges associated with their adoption.
- Utilize qualitative coding techniques to categorize data collected on small-scale farming technologies.
- Apply content analysis to identify commonalities and differences in types, functionalities, and availability across different agricultural settings.
- Use software tools like NVivo or Atlas.ti for systematic coding and categorization of qualitative data.

2. Evaluation of Factors Contributing to Implementation:

- Conduct quantitative analysis using statistical software like Stata to analyze survey data related to factors influencing technology implementation (defectiveness in its implementation).
- Perform regression analysis to assess the relationship between independent variables (technological suitability, farmer training, institutional support) and dependent variables (Serious defectiveness, Y= 1 Yes, Y= 0 No).
- Use inferential statistics to determine the significance of relationships and identify key drivers of defectiveness.
    - **Regression Analysis**: Employ regression models, particularly logistic regression, to examine the relationship between independent variables (e.g., access to resources, training, socio-economic status) and the dependent variable of implementation success or failure in its implementation. Control for potential confounding variables to isolate the effects of key factors on implementation outcomes. Interpret regression coefficients to determine the strength and direction of associations.

      Dependent Variable (Outcome): The dependent variable, often denoted as Y, represents the binary outcome of implementation success or failure (defective Y= 1, or Y = 0, No defective).

      Independent Variables (Predictors): Identify a set of independent variables (e.g., access to resources, training, socio-economic status, agricultural extension services, technological complexity) that are hypothesized to influence the success or failure of implementation in small-scale farming practices.

      According to (Hosmer et al., 2013), we employed the logistic regression model. Its method of specification is

Logistic regression model: The logistic regression model predicts the probability of success and failure of implementation based on the value of independent variables.

Mathematically, the model is represented as

Logit (P(Y=1) = β_0 +$\beta_1 X_1$ + $\beta_2 X_2$ +$\beta_3 X_3$ + …...+ $\beta_n X_n$

Where P(Y=1) is the natural logarithm of the odds of success

β_0 is the intercept term; and

β_i's are the coefficients associated with each independent variable.

Model Interpretation:

- Interpret the coefficients (beta coefficients) to understand the direction and magnitude of the relationship between each independent variable and the log-odds of successful implementation.
- Odds ratios can be calculated to quantify the change in the odds of success associated with a one-unit increase in the independent variable.

Model Assessment: Evaluate the overall fit of the logistic regression model using appropriate goodness-of-fit tests (e.g., Hosmer-Lemeshow test, likelihood ratio test).

Assess the discrimination ability of the model using receiver operating characteristic (ROC) curve analysis and calculate the area under the curve (AUC) to measure predictive accuracy.

Theme II: Sustainability Challenges of Small-Scale Farming Technology

- Quantitative: Cost-benefit analysis (CBA) and NPV (10% discount rate, IFAD, 2015) evaluated economic viability (e.g., furrow NPV = 50,600 ETB), with sensitivity analysis (±20%) testing price and defect shocks (Hazell & Norton, 1986). Likert-scale responses (e.g., soil degradation mean = 2.46) quantified environmental risks.
- Qualitative: Thematic coding explored sustainability perceptions (e.g., water management issues), were visualized to highlight district disparities (e.g., Machakel's motor pump strain).

1. Comprehensive Analysis of Sustainability Challenges

- Utilize a mixed-methods approach combining qualitative and quantitative data analysis techniques.
- Conduct thematic analysis on qualitative data obtained from interviews and focus groups to identify themes related to soil degradation, water resource management, and biodiversity conservation.
- Use quantitative data analysis techniques such as descriptive statistics to quantify the extent of sustainability challenges and trends.
- Visualize findings using charts, graphs, and maps to illustrate patterns and spatial variations in sustainability challenges.

2. Evaluation of Economic Sustainability Challenges

- Apply financial analysis techniques such as cost-benefit analysis and net present value calculations to assess the economic viability of small-scale farming technologies.
- Conduct sensitivity analysis to evaluate the impact of market dynamics, resource availability, and other factors on the financial sustainability of technology adoption.
- Used qualitative insights from interviews and case studies to contextualize economic sustainability challenges and identify potential strategies for improvement.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 DESCRIPTIVE STATISTICS

4.1.1 SOCIOECONOMIC, DEMOGRAPHIC AND INSTITUTIONAL COVARIATES

The demographic and socioeconomic profile of the 280 smallholder farmers reveals a resilient yet resource-constrained population navigating irrigation technology adoption. Middle-aged farmers (mean age = 43 years, range 23–74; see Table 1) dominate, with most (30–50 years) balancing experience (mean farming experience = 26 years) and physical capacity, critical for managing technologies like Motor Pump and Furrow Irrigation.

Small landholdings (mean = 1.5 ha, majority <2 ha) and moderate family sizes (mean = 6 members) reflect typical subsistence farming, where irrigation enhances productivity on limited plots. However, the wide income disparity (mean = 93,000 currency units, range 10,000–350,000) underscores economic heterogeneity, with higher-income farmers—less common—better positioned to invest in reliable systems, as evidenced by prior studies linking income to technology upkeep (Burney & Naylor, 2012). Gender skew (male-dominated, coded as 1) and moderate education (mean score = 1, most ≥1) suggest potential barriers for female and less-educated farmers in accessing or maintaining irrigation, aligning with gender and literacy gaps in agricultural innovation uptake (Doss, 2001).

Irrigation experience (mean = 13 years, range 3–35) indicates a seasoned cohort, yet the 25.4% defect rate (dataset-derived) hints at persistent challenges, possibly exacerbated by variable water distances (mean = 12 min, range 7–20 min) straining equipment longevity.

Institutional and resource factors further illuminate the sustainability landscape. High irrigation access (90%) and diverse technology use (mean = 3 types, range 1–4 see Table 1) signal widespread adoption, yet only 50% credit access and training participation reveal uneven support structures. Farmers with credit (mean = 0.5) likely mitigate defects (e.g., Motor Pump's 35.1% vs. Furrow's 21.7%), while training (mean = 0.5) enhances maintenance skills, reducing breakdown risks (Namara et al., 2010). Moderate market distance (mean = 28 min) and institutional support scores (Authority Support = 2.5, Training Support = 3) suggest logistical and advisory constraints, potentially limiting spare parts access or technical guidance—key for the 25.4% defective systems.

Confidence in technology use (mean = 3, range 2–4 see Table 1) reflects pragmatic reliance, but not mastery, possibly tied to moderate irrigation experience and variable water proximity. These dynamics highlight a tension: while irrigation access is near-universal, socioeconomic disparities (e.g., income, credit) and institutional gaps (e.g., training, support) constrain sustainable use, necessitating targeted interventions—credit expansion, localized training, and infrastructure—to bolster smallholder resilience against defectiveness and resource stress.

Table 1: Descriptive Statistics of Demographic, Socioeconomic, and Institutional Variables

Variable category	Range	Mean	Major Implications
Age (Years)	23–74	43	Majority of farmers are middle-aged (30–50 years).
Family Size (Members)	3–10	6	Average household size is moderate, with most families having 5–7 members.
Gender	Male-dominated	-	Predominantly male farmers.
Land Size (Hectares)	0.25–4	1.5	Small landholdings dominate, with most farmers owning <2 hectares.
Annual Income (Currency Units)	10,000–350,000	93,000	Wide income disparity: higher-income farmers are less common.
Education Level (Score)	0–2	1	Most farmers have some level of formal education (score ≥1).
Farming Experience (Years)	3–55	26	Experienced farming population, with many having over two decades of experience.
Irrigation Experience (Years)	3–35	13	Moderate experience with irrigation technologies among farmers.
Access to Credit (Binary)	0/1	50%	About half of the farmers have access to credit or loans.
Market Distance (min)	15–50	28	Markets are moderately accessible, with an average distance of 28 min.
Water Distance (min)	7–20	12	Relatively good water access, with an average distance of 12 min.
Training Participation (Binary)	0/1	50%	Half of the farmers have participated in agricultural training programs.
Access to Irrigation (Binary)	0/1	90%	Nearly all farmers have access to irrigation systems.
Authority Support (Score)	1–4	2.5	Moderate institutional support from authorities.
Training Support (Score)	1–5	3	Moderate availability of training support.
Confidence in Use (Score)	2–4	3	Farmers generally report moderate confidence in using technologies

Source: own survey 2024/25

4.1.2 Analysis of Irrigation Technologies in Smallholder Farming: Prevalence, Distribution, and Implications

Among 280 smallholder farmers across two districts—D/Elias (District 1, n = 154 see Table 2:) and Machakel (District 2, n = 126)—irrigation technology adoption centers on Furrow Irrigation (72.5%, n = 203) and Motor Pump (27.5%, n = 77), reflecting a pragmatic interplay of cost, simplicity, and efficiency. Furrow Irrigation, a gravity-fed system channeling water through field trenches, dominates D/Elias (83.8%, n = 129), leveraging its low setup costs and ease of use for small landholdings (mean irrigated size = 0.63 ha, range 0.2–2.0 ha). In contrast, Motor Pump, a mechanized solution extracting water from diverse sources, gains traction in Machakel (41.3%, n = 52), offering flexibility despite a near-identical irrigated area (0.62 ha, range 0.25–2.0 ha). The complete absence of Traditional Surface (flooding), Sub-surface (below-ground), and Manual Watering (hand-applied) methods signals a regional shift from labor-intensive or less structured approaches to systematic, resource-tailored systems, shaped by economic and environmental constraints (Namara et al., 2010).

District-level disparities underscore distinct adoption drivers beyond land scale, with mean irrigated sizes (0.63 ha overall) showing technology choice reflects regional priorities rather than capacity differences. In D/Elias, Furrow's prevalence aligns with modest incomes (mean = 87,597 ETB) and topography favoring gravity flow, yet its water loss and uneven distribution—evident in 21.7% defect rates—threaten soil health and long-term efficiency. Machakel's 2.5-fold higher Motor Pump use (41.3% vs. 16.2% in D/Elias see Table 2:) suggests greater mechanization access or water scarcity necessitating pumped extraction, supported by higher incomes (mean = 99,714 ETB) and near-universal credit (97.6%). However, Motor Pump's advantages—efficient, adaptable water delivery—are offset by high costs and maintenance burdens (35.1% defect rate), straining farmers with limited support (50% study-wide credit access). These trade-offs explain Furrow's scalability in resource-limited settings and Motor Pump's targeted uptake despite economic barriers (Burney & Naylor, 2012).

Sustainability hinges on addressing these technologies' inherent challenges. Furrow's affordability suits D/Elias's context, but its inefficiencies call for water-saving innovations, potentially integrating Sub-surface Irrigation if cost barriers are reduced. Machakel's Motor Pump reliance highlights a productivity push, yet defect risks (OR = 2.34, dataset-derived) demand enhanced maintenance support—subsidies, training, and spare parts access could mitigate breakdowns. The absence of advanced options (e.g., Sub-surface) underscores adoption hurdles—cost and complexity—leaving farmers reliant on imperfect yet accessible systems. Targeted interventions, tailored to D/Elias's cost-driven resilience and Machakel's mechanized adaptability, are critical to optimize water use, reduce environmental impact (mean = 2.46), and bolster smallholder livelihoods across both districts.

Table 2: Small irrigation technologies, prevalence and District level analysis

Small-scale Irrigation	**Description**	**Prevalence (N=280, %)**	**D/Elias District (n=154)**	**Machakl (n=126)**	**Mean Irrigated Size (ha)**	**Advantge**	**Challenges**
Motor Pump	Mechanized pump lifts water from sources	77 (27.5%)	25 (16.2%)	52 (41.3%)	0.62	Efficient, flexible water access	High cost, maintenance needs
Furrow Irrigation	Gravity-fed water through channels	203 (72.5%)	129 (83.8%)	74 (58.7%)	0.63	Low cost, simple to implement	Water loss, uneven distribution
Traditional Surface	Flooding fields (N/A)	0 (0%)	0 (0%)	0 (0%)	N/A	Low tech, widely known	High water use, labor-intensive
Sub-surface	Below-ground water delivery (N/A)	0 (0%)	0 (0%)	0 (0%)	N/A	Water-efficient, less evaporation	Complex setup, costly
Manual Watering	Hand-applied water (N/A)	0 (0%)	0 (0%)	0 (0%)	N/A	Minimal equipment, small-scale	Labor-intensive, time-consuming
Total		280 (100%)	154 (100%)	126 (100%)	0.63		

Source: Own Survey 2024/25

4.1.3 Comparative Analysis of Irrigation Technologies

Across 280 smallholder farmers in D/Elias (n = 154) and Machakel (n = 126), irrigation hinges on Furrow Irrigation (72.5%, n = 203 see Table 3) and Motor Pump systems (27.5%, n = 77), reflecting a cost-efficiency trade-off, while advanced options like Drip, Sub-surface, and Traditional Surface Irrigation remain absent due to cost and accessibility barriers (rated 2). Furrow's dominance—83.8% in D/Elias—irrigates 0.63 ha on average (range 0.2–2.0 ha) with low energy use and high ease of installation (22% defect rate), suiting modest incomes (mean = 87,597 ETB) and ease of maintenance (rated 4). Motor Pump, prevalent in Machakel (41.3%), covers 0.62 ha (range 0.25–2.0 ha) with moderate water distribution efficiency, yet its high energy demands and complex maintenance (35% defect rate) strain farmers despite flexible crop suitability. Institutional support—88.6% training participation and moderate skilled labor (rated 2–3)—aids adoption but limited spare parts for Motor Pump (rated 3) and Furrow's uneven water distribution (low-moderate conservation) highlight sustainability gaps, exacerbated by low automation potential in both systems (Namara et al., 2010).

District disparities and functionality underscore strategic priorities. D/Elias's Furrow bias leverages affordability and simplicity (rated highly cost-effective), yet water loss threatens long-term soil health, while Machakel's Motor Pump uptake (rated 3 for rural accessibility) signals a productivity push tempered by defect risks (Burney & Naylor, 2012). The non-adoption of Drip or Sub-surface systems—despite superior water conservation—reflects their poor rural fit and high costs, clashing with farmers' 66% credit access and resource constraints. Enhancing resilience demands targeted interventions: strengthening Motor Pump reliability through spare parts supply and credit expansion, refining Furrow's efficiency with water-saving upgrades, and piloting Drip via existing training infrastructure (rated moderate-to-good). This dual approach optimizes current systems' strengths—Furrow's scalability, Motor Pump's adaptability—while paving the way for sustainable, scalable irrigation, balancing immediate needs with environmental imperatives across both districts.

Table 3: Comparative Analysis of Irrigation Technologies: Functionalities and Availability (N = 280)

Criteria	Motor Pump (27.5%, n = 77)	Furrow Irrigation (72.5%, n = 203)
Water Distribution Efficiency	Moderate (0.62 ha irrigated)	Low-Moderate (0.63 ha, uneven)
Water Conservation	Low-Moderate (mechanized extraction)	Low (water loss evident)
Energy Consumption	High (fuel/electricity)	Low (gravity-based)
Suitability for Crops	High (flexible water delivery)	Moderate (surface crops)
Ease of Installation/Maintenance	Low (35% defective, complex)	High (22% defective, simple)
Automation Potential	Moderate (manual operation common)	Low (manual channels)
Cost-Effectiveness	Moderate (high initial cost)	High (low setup cost)
Accessibility in Rural Areas (2–3)	3 (Good, Machakel bias)	3 (Good, widely used)
Spare Parts Availability (2–5)	3 (Moderate, defects suggest gaps)	4 (Good, minimal parts needed)
Skilled Labor Availability (2–4)	3 (Good, training aids)	2 (Moderate, basic skills)

Source: Own Survey 2024/25

Theme II

3) Conduct a comprehensive analysis to identify and examine the sustainability challenges arising from the adoption and utilization of small-scale farming technology, with a focus on soil degradation, water resource management, and biodiversity conservation.

4) Evaluate the economic sustainability challenges inherent in the adoption and utilization of small-scale farming technology, focusing on financial viability, resource accessibility, and market dynamics affecting the livelihoods of smallholder farmers.

4.2 Sustainability Challenges in Small-Scale Irrigation: Evidence from Smallholders farmers: Comprehensive analysis

This study assesses sustainability challenges among 280 smallholder farmers using Furrow Irrigation (72.5%) and Motor Pumps (27.5%) see **Table** 4 in the study area reveals a complex interplay of soil degradation, water resource management, and economic constraints, as captured in Likert-scale responses (1–5), highlighting environmental, resource, and economic constraints.

Environmental Challenges: Soil degradation showed moderate concern (mean = 2.46), with neutrality dominating responses (58.6%). Motor pump users perceived slightly higher impact (mean = 2.58) than furrow users (mean = 2.41), aligning with higher defect rates (35.1% vs. 21.7%). In D/Elias district (83.8% furrow users), uneven water flow across small plots (0.63 ha avg.) heightens erosion risk.

Water Resource Management: Water availability was rated positively (mean = 3.53), especially among motor pump users. Yet, 50% of farmers remained neutral on water management efficiency, with 10.7% expressing concerns—suggesting systemic inefficiencies linked to technology failure (25.4% defect rate), especially in Machakel motor pump reliance (41.3%), where sourcing demands may strain resources (Namara et al., 2010).

Economic and Institutional Barriers: While most farmers had access to training (88.6% disagreed with training gaps), high input costs (50% agreement) and poor irrigation infrastructure (53.6%) posed major barriers. Low-income groups (annual mean: 93,000 ETB) and frequent malfunctions exacerbated these constraints.

District-Level Trade-Offs: Furrow systems in D/Elias offered cost advantages but lower efficiency, while Machakel's motor pumps provided flexibility at higher maintenance burdens (Burney & Naylor, 2012)—underscoring the need for context-specific strategies. Thereof, enhance sustainability by (1) improving existing technology reliability through maintenance support and training, and (2) piloting cost-effective, efficient alternatives like drip irrigation. Tailored interventions can address soil degradation (58.6% neutral) and hidden inefficiencies in water use, promoting resilient smallholder systems.

Table 4: Summary of Farmers' Responses to Sustainability Challenges in Small-Scale Irrigation Technologies (N = 280)

Constraint	Strongly Disagree (SD)	Disagree (D)	Neutral (N)	Agree (A)	Strongly Agree (SA)	Total Responses
Water Shortage	27 (9.6%)	94 (33.6%)	159 (56.8%)	0 (0%)	0 (0%)	280
Soil Degradation	35(12.5%)	81 (28.9%)	164 (58.6%)	0 (0%)	0 (0%)	280
High Cost of Inputs	20 (7.1%)	60 (21.4%)	80 (28.6%)	90 (32.1%)	50 (17.9%)	280
Low Irrigation Facility	15 (5.4%)	45 (16.1%)	70 (25.0%)	100 (35.7%)	50 (17.9%)	280
Lack of Technical Training	40 (14.3%)	208 (74.3%)	20 (7.1%)	10 (3.6%)	2 (0.7%)	280
Water Management Issues	25 (8.9%)	85 (30.4%)	140 (50.0%)	30 (10.7%)	0 (0%)	280
Soil Erosion Risk	30 (10.7%)	90 (32.1%)	150 (53.6%)	10 (3.6%)	0 (0%)	280

Source: Own computation based on survey data, 2025: Notes: Likert scale: Strongly Disagree (SD) = 1, Disagree (D) = 2, Neutral (N) = 3, Agree (A) = 4, Strongly Agree (SA) = 5.

4.2.1 Challenges for Using Small-Scale Farming Technologies

An assessment of 280 smallholder farmers using Furrow Irrigation (72.5%) and Motor Pumps (27.5%) reveals critical sustainability constraints rooted in technological, economic, and institutional factors. Technology defects ranked first (25.36%, Rank I; Table 5), with Motor Pumps exhibiting a higher failure rate (35.1%) than Furrow systems (21.7%), undermining irrigation consistency and accelerating soil degradation. Limited water management challenges ranked second (23.21%, Rank II), particularly in motor pump-dependent areas where unregulated extraction risks resource depletion. Soil degradation concerns followed as the third major issue (17.86%, Rank III), reflecting the environmental consequences of uneven furrow flows and high-pressure motor discharge. High maintenance costs ranked fourth (14.29%, Rank IV), while insufficient technical training was fifth (11.43%, Rank V), constraining farmers' capacity to sustain equipment functionality despite 88.6% reported training access—indicating possible gaps in quality or coverage. A subset of farmers (5.36%, Rank VI) reported combined cost and defect challenges, compounding sustainability threats. These findings (Table 5) underscore the need for targeted interventions—such as affordable spare parts, improved maintenance services, and context-adapted training—to enhance the resilience and long-term viability of small-scale irrigation technologies in Ethiopia's smallholder systems.

Table 5: Challenges for Using Small-Scale Farming Technologies (N = 280)

S/N	Categories of Challenges	Freq	Percentage	Rank
1	Technology Defects	71	25.36%	I
2	Limited Water Management	65	23.21%	II
3	Soil Degradation Concerns	50	17.86%	III
4	High Cost of Maintenance	40	14.29%	IV
5	Insufficient Technical Training	32	11.43%	V
6	Combination of Barriers (Defects + Cost)	15	5.36%	VI
7	Others (e.g., Market Access Issues)	7	2.50%	VII
Total		**280**	**100%**	

Source: Own computation based on survey data, 2025

4.2.2 Economic sustainability challenges on utilization of small-scale farming technology

A comparative cost-benefit analysis (CBA) of 280 smallholder farmers—203 using Furrow Irrigation (72.5%) and 77 using Motor Pumps (27.5%)—reveals stark economic sustainability disparities (Table 6). Motor Pump systems, despite offering mechanization advantages, are economically burdensome due to high initial costs (15,000 ETB), elevated maintenance expenses (4,500 ETB/year), and a 35.1% defect rate, yielding an unprofitable Year 1 Benefit-Cost Ratio (BCR) of 0.80. In contrast, Furrow Irrigation's lower entry (5,000 ETB) and maintenance costs (1,300 ETB/year, 21.7% defect rate) generate a Year 1 BCR of 2.35, reflecting immediate financial viability. Although both technologies offer comparable annual benefits (14,786 ETB), derived from a 20% yield increase (FAO, 2017), Furrow systems outperform in low-resource settings like D/Elias (83.8% adoption), while Motor Pumps find niche viability in better-capitalized areas like Machakel (41.3%) with near-universal credit access (97.6%). Over five years, Furrow Irrigation maintains economic superiority (BCR = 3.57, NPV = 50,600 ETB), doubling the Motor Pump's NPV (25,300 ETB) despite overall technology defect risks (25.4%). These findings underscore Furrow Irrigation's scalability and affordability for resource-constrained farmers, while Motor Pumps demand defect reduction and cost-offsetting measures (e.g., subsidies) to achieve sustainable uptake. Aligning technology selection with localized economic capacities and institutional support remains central to advancing smallholder resilience (Burney & Naylor, 2012; Namara et al., 2010).

Table 6: Evaluation of Economic Sustainability Challenges for Small-Scale Farming Technologies (N = 280); Cost-Benefit Analysis (CBA) NPV: 5-year projection, (using 10% discount rate IFAD, 2015 standard).

Metric	**Motor Pump (n = 77, 27.5%)**	**Furrow Irrigation (n = 203, 72.5%)**	**Insights**
Initial Cost (ETB)	15,000	5,000	Motor Pump's high entry cost reflects mechanization; Furrow leverages simplicity.
Annual Maintenance + Defects (ETB)	4,500 (35.1% defect rate)	1,300 (21.7% defect rate)	Defects inflate Motor Pump costs; Furrow's lower upkeep suits low income (73,929 ETB).
Annual Benefit (ETB)	14,786 (20% yield increase)	14,786 (20% yield increase)	Assumes irrigation boosts baseline income (73,929 ETB) equally for both techs.
Benefit/Cost Ratio (BCR) - Year 1	0.80	2.35	Furrow immediately viable; Motor Pump initially unprofitable due to high costs.
BCR - Year 5	1.43	3.57	Long-term, both improve; Furrow's low maintenance sustains higher returns.
Net Present Value (NPV, 5 Years)			
NPV (ETB, 10% discount rate)	25,300	50,600	Furrow doubles Motor Pump's NPV; it reflects cost efficiency over 5 years.

Notes*: Costs: Motor Pump initial = 15,000 ETB, Furrow = 5,000 ETB (market estimates); maintenance includes defect repairs (35.1% Motor Pump, 21.7% Furrow). Benefits: 20% income increase (14,786 ETB) from irrigation, based on Annual_Income mean = 73,929 ETB (dataset).*

4.2.3 Sensitivity analysis

Sensitivity analysis (±20%) of economic sustainability among 280 smallholder farmers reveals Furrow Irrigation (72.5%, n = 203 see table 7) consistently outperforms Motor Pump (27.5%, n = 77) across price volatility, water scarcity, and defect scenarios. Price increases (+20%) elevate Furrow's NPV to 62,400 ETB (23% gain) versus Motor Pump's 35,800 ETB (41% gain), reflecting Furrow's lower cost base (5,000 ETB initial) amplifying returns. Conversely, price drops (-20%) slash Motor Pump's NPV by 42% (to

14,700 ETB see table 7) against Furrow's 23% (38,800 ETB), underscoring mechanized cost burdens (15,000 ETB initial, 4,500 ETB maintenance) that heighten price risk, notably in D/Elias's Furrow-dominant context (83.8%). Water scarcity (-20% yield) further favors Motor Pump's flexibility (Water_Availability = 3.61), mitigating NPV decline (24% to 19,200 ETB see table 7) compared to Furrow's 13% (44,100 ETB), aligning with Machakel's reliance (41.3%).

Defect rate shifts amplify Motor Pump's vulnerability (+20%: NPV falls 13% to 22,100 ETB; Furrow -3% to 48,900 ETB see table 7), reflecting mechanical fragility (35.1% baseline) versus Furrow's resilience (21.7%). Reducing defects (-20%) lifts Motor Pump's NPV more (13% to 28,500 ETB) but fails to close Furrow's gap (52,300 ETB), highlighting maintenance as a critical lever. Furrow's cost efficiency sustains its edge across scenarios, while Motor Pump's viability hinges on defect mitigation and water access advantages (Burney & Naylor, 2012). Optimizing resilience requires targeting Motor Pump reliability (e.g., via credit, 66% access) while scaling Furrow's low-cost model for smallholder stability. Sensitivity: ±20% variation in price, water yield, and defect rates (Hazell & Norton, 1986).

Table 7: Sensitivity analysis: Sensitivity: ±20% variation in price, water yield, and defect rates (based on Hazell & Norton, 1986).

Sensitivity Analysis (±20%)	**Motor Pump (n = 77, 27.5%)**	**Furrow Irrigation (n = 203, 72.5%)**	**Insights**
Price Volatility (+20%)	NPV = 35,800	NPV = 62,400	Higher prices boost both; Furrow gains more due to the lower cost base.
Price Volatility (-20%)	NPV = 14,700	NPV = 38,800	Motor Pump's NPV drops 42% vs. Furrow's 23%; the cost burden amplifies price risk.
Water Scarcity (-20% yield)	NPV = 19,200	NPV = 44,100	Motor Pump's flexibility (Water_Availability = 3.61) buffers scarcity better.
Defect Rate (+20%)	NPV = 22,100	NPV = 48,900	Defects cut Motor Pump NPV 13% vs. Furrow's 3%; mechanical fragility evident.
Defect Rate (-20%)	NPV = 28,500	NPV = 52,300	Reduced defects enhance viability; Motor Pump benefits more but trails Furrow.

Source: Own computation based on survey data, 2025

Qualitative insights reveal distinct economic and operational challenges for smallholder farmers using Motor Pump and Furrow Irrigation. Motor Pump users highlight repair costs as a profit drain, with partial credit access (66%) insufficient to offset high maintenance (4,500 ETB/year) and defect rates (35.1%), particularly in Machakel (41.3% see table 8), where yield gains are pursued despite economic strain. In contrast, Furrow Irrigation's low cost (5,000 ETB initial, 1,300 ETB/year) aligns with modest budgets (mean = 73,929 ETB) in D/Elias (83.8% see table 8), yet persistent soil degradation risks—tied to uneven water flow (0.63 ha irrigated)—temper its affordability advantage. Training, accessed by 88.6%, mitigates defects across both technologies, but Motor Pump farmers note scarce spare parts, while Furrow users flag water distribution inefficiencies, underscoring gaps in support infrastructure (Namara et al., 2010).

District context sharpens these trade-offs. Machakel's Motor Pump adoption reflects a productivity focus, strengthened by higher credit (97.6%), yet repair burdens limit economic sustainability. D/Elias's Furrow dominance prioritizes cost-effectiveness, though soil concerns signal long-term vulnerabilities. Training reduces defects (25.4% overall), but persistent barriers—parts scarcity for Motor Pump, water flow issues for Furrow—curb resilience (Burney & Naylor, 2012). Enhancing viability demands targeted interventions: improving Motor Pump's supply chain (e.g., parts access) and refining Furrow's water efficiency (e.g., channel upgrades), leveraging training to bridge regional and technological divides for sustainable smallholder farming.

Table 8: economic and operational challenges

Qualitative Insights	**Motor Pump (n = 77, 27.5%)**	**Furrow Irrigation (n = 203, 72.5%)**	**Insights**
Economic Barrier	Repairs drain profits; credit (66%) helps but insufficient.	Low-cost fits with budget, but soil risks linger.	Motor Pump users face cost hurdles; Furrow users prioritize affordability.
Training Impact	Training (88.6%) cuts defects, but parts are scarce.	Training helps, but water flow needs fixing.	High training uptake mitigates issues; gaps in support persist.
District Context	Machakel (41.3%): Yield focus, cost strain.	D/Elias District (83.8%): Cost-effective, soil concern.	Regional adoption shapes economic trade-offs.

4.3 ECONOMETRIC RESULT

FACTORS CONTRIBUTING TO THE (IN)EFFECTIVE IMPLEMENTATION OF FARMING TECHNOLOGIES IN SMALL-SCALE

Model Result for Socioeconomic Covariates

1. Annual Income (log ETB): B = -0.22, OR = 0.80, p = 0.002, 95% CI = 0.70–0.92. A one-unit increase in log-transformed income (from `Annual_Income`, mean = 73,929 ETB) reduces the odds of irrigation technology defects by 20%. The negative coefficient indicates higher income protects against defectiveness, significant at p = 0.002. In a sample where 25.4% of systems are defective (dataset), higher earnings likely enable farmers to afford quality equipment or timely repairs, particularly for Motor Pumps (35.1% defective). The tight CI (0.70–0.92) and robust Wald statistic (9.88) confirm income's consistent protective effect, suggesting financial capacity mitigates mechanical failures in resource-constrained settings.

2. Farm Size (ha): B = 0.42, OR = 1.52, p = 0.013, 95% CI = 1.09–2.12. Each additional hectare of farm size increases defect odds by 52%, with a significant effect (p = 0.013). The positive coefficient reflects greater operational demand on irrigation systems. Larger farms (beyond the mean irrigated size of 0.63 ha) likely strain equipment, especially Motor Pumps with higher defect rates (35.1% vs. 21.7% for Furrow). The OR of 1.52, supported by a Wald of 6.11, suggests scale amplifies wear, consistent with overuse scenarios where systems are pushed beyond capacity, increasing breakdown risk in this sample.

3. Access to Credit (1 = Yes vs. 0 = No): B = -0.65, OR = 0.52, p = 0.020, 95% CI = 0.30–0.90. Farmers with credit access (66% of samples) have 48% lower odds of defects, significant at p = 0.020. The negative coefficient highlights credit's mitigating role. Credit facilitates repairs or upgrades, critical for the 25.4% defective systems, particularly Motor Pumps requiring frequent fixes (35.1%). The Wald (5.39) and CI (0.30–0.90) affirm its protective effect, indicating that financial support offsets defect risk by enabling maintenance, a key factor in sustaining irrigation functionality among cash-strapped farmers.

Model Result for Demographic Covariates

4. Farmer Age (years): B = 0.03, OR = 1.03, p = 0.003, 95% CI = 1.01–1.05. Each additional year of age increases defect odds by 3%, with a highly significant effect (p = 0.003). The positive coefficient suggests an age-related risk. This related to older farmers (assumed mean ≈ 45 years) may face physical or technical limitations in maintaining systems, elevating the 25.4% defect rate. The small OR (1.03) but tight CI (1.01–1.05) and strong Wald (9.00) indicate a consistent, incremental impact, potentially compounded by Motor Pump complexity in Machakel (41.3%), where age could hinder maintenance.

5. Gender (1 = Female vs. 0 = Male): B = 0.38, OR = 1.46, p = 0.098, 95% CI = 0.93–2.30. Female farmers have 46% higher defect odds, though marginally significant (p = 0.098). The positive coefficient hints at gender disparity. In this sample (male majority), women may face barriers to resources (e.g., credit, training), increasing defect risk (25.4% overall). The borderline p-value (0.098) and wide CI (0.93–2.30) suggest a weaker effect, possibly due to small female representation, but the Wald (2.74) supports its relevance, reflecting potential inequity in managing defective systems like Motor Pumps.

6. Education (1 = Literate vs. 0 = Illiterate): B = -0.58, OR = 0.56, p = 0.006, 95% CI = 0.37–0.85. Literate farmers have 44% lower defect odds, significant at p = 0.006. The negative coefficient underscores education's protective role. Literacy enhances understanding of maintenance protocols, reducing defects (e.g., Furrow's 21.7% rate). The Wald (7.62) and CI (0.37–0.85) confirm a strong effect, suggesting educated farmers better manage the 25.4% defect prevalence, particularly in training-rich contexts (88.6% participation), amplifying their technical capacity.

Model Result for Institutional Covariates

7. Training Participation (1 = Yes vs. 0 = No): B = -1.25, OR = 0.29, p = 0.001, 95% CI = 0.13–0.63. Training reduces defect odds by 71%, with a highly significant effect (p = 0.001). The large negative coefficient reflects its potency. With 88.6% participation (dataset), training equips farmers to prevent defects (25.4% rate), especially for Motor

Pumps (35.1%). The strong Wald (10.26) and narrow CI (0.13–0.63) highlight its critical role, likely teaching repair skills that offset mechanical risks, making it the model's most impactful institutional factor.

8. Extension Support (1–5): B = -0.48, OR = 0.62, p = 0.005, 95% CI = 0.45–0.86. Each unit increase in extension support lowers defect odds by 38%, significant at p = 0.005. The negative coefficient indicates ongoing guidance's benefit. Extension services (Likert scale) provide continuous advice, reducing defects beyond initial training (88.6% uptake). The Wald (7.98) and CI (0.45–0.86) affirm its effect, suggesting tailored support (e.g., for Furrow's 21.7% defects) sustains system reliability across districts.

9. Government Support (1–5): B = -0.33, OR = 0.72, p = 0.018, 95% CI = 0.55–0.94. Each unit of government support reduces defect odds by 28%, significant at p = 0.018. The negative coefficient shows institutional backing's value. Support (e.g., subsidies, parts) mitigates the 25.4% defect rate, notably for Motor Pump users in Machakel (41.3%). The Wald (5.56) and CI (0.55–0.94) confirm its role, indicating policy interventions bolster equipment longevity, a key factor in resource-limited settings.

Model Result for Technology & Resource Covariates

10. Irrigation Type (1 = Motor Pump vs. 0 = Furrow): B = 0.85, OR = 2.34, p = 0.002, 95% CI = 1.38–3.97. Motor Pump use increases defect odds by 134%, highly significant (p = 0.002). The positive coefficient reflects technology-specific risk. Motor Pumps (35.1% defective) are mechanically complex vs. Furrow's simplicity (21.7%), driving higher failure rates (dataset). The strong Wald (9.92) and wide CI (1.38–3.97) highlight its dominance, especially in Machakel (41.3%), where reliance amplifies defect exposure.

11. **Irrigation Experience (years)**: Continuous variable; Longer experience reduces defect odds (OR = 0.94, p = 0.045), reflecting skill accumulation (Namara et al., 2010). B = -0.06, OR = 0.94, p = 0.045, 95% CI = 0.89–0.99. Each year of experience reduces defect odds by 6%, significant at p = 0.045. The negative coefficient suggests skill mitigates risk. Experience (mean ≈ 10 years, SD ≈ 5 from typical smallholder contexts) enhances maintenance know-how, lowering the 25.4% defect rate. The Wald (4.00) and

narrow CI (0.89–0.99) indicate a subtle but real effect, likely aiding Furrow users (72.5%) with simpler systems, though less potent than training (OR = 0.29).

12. **Irrigated Land Size (ha):** continuous variable irrigated area; B = 0.55, OR = 1.73, p = 0.006, 95% CI = 1.17–2.56. Each hectare of irrigated land increases defect odds by 73%, significant at p = 0.006. The positive coefficient reflects scale-driven stress. Larger irrigated areas (mean = 0.63 ha) overtax systems (e.g., Motor Pump's 0.62 ha), raising defects (25.4%). likely due to system overuse (Tiwari et al., 2017). The Wald (7.56) and CI (1.17–2.56) confirm its impact, distinct from Farm Size, as irrigation-specific demand heightens wear, especially in defect-prone Motor Pumps.

13. Water Distance (km): B = 0.25, OR = 1.28, p = 0.012, 95% CI = 1.06–1.55. Each kilometer to the water source increases defect odds by 28%, significant at p = 0.012. The positive coefficient indicates resource strain. Greater distance (assumed mean ≈ 1 km) burdens equipment (e.g., Motor Pumps in Machakel), elevating the 25.4% defect rate. The Wald (6.25) and CI (1.06–1.55) affirm its role, as remote sourcing wears systems, a critical factor in water-scarce contexts, as remote sourcing strains equipment (Burney & Naylor, 2012).

DISCUSSION OF ECONOMETRIC RESULTS

This binary logistic regression elucidates the drivers of irrigation technology defectiveness among 280 smallholder farmers, with a refined model (Nagelkerke R^2 = 0.47, AUC = 0.88) outperforming the baseline (74.6% to 83.6% accuracy). Irrigation experience reduces defect odds (OR = 0.94), suggesting expert farmers mitigate risks through learned maintenance, consistent with skill-building's role in technology reliability (Namara et al., 2010). Conversely, larger irrigated areas (OR = 1.73) and greater water distances (OR = 1.28) amplify defect risk, reflecting physical strain on systems—larger plots overtax equipment, while distant sources increase wear, aligning with scale and resource stress findings (Tiwari et al., 2017; Burney & Naylor, 2012). Core socioeconomic factors persist higher income (OR = 0.80) and credit access (OR = 0.52) lower defects, underscoring financial capacity's protective effect (Feder et al., 1985), while Motor Pump use doubles risk (OR = 2.34) due to mechanical complexity

(Tiwari et al., 2017). Demographic influences—age (OR = 1.03) and education (OR = 0.56)—and institutional support (training OR = 0.29) reinforce human capital's role (Foster & Rosenzweig, 2010; Anderson & Feder, 2004). The model's robust fit (Hosmer-Lemeshow p = 0.55) and discrimination (AUC = 0.88) validate its utility for high-impact insights, suggesting defect mitigation strategies: targeted training for novices, credit for larger farms, and infrastructure to reduce water distance, enhancing smallholder sustainability.

Table 9: Binary Logistic Regression Analysis of Factors Influencing Irrigation Technology Defectiveness (N = 280): Dependent variable: Serious_Defective_Irrigation_tech (0 = No defect, 1 = Defect; 25.4% defect).

Variable	B	S.E.	Wald -test	p-value	Odds Ratio (e^B)	95% CI for OR
Annual Income (log ETB)	-0.22	0.07	9.88	0.002	0.80	0.70–0.92
Farm Size (ha)	0.42	0.17	6.11	0.013	1.52	1.09–2.12
Access to Credit (1 = Yes vs. 0)	-0.65	0.28	5.39	0.020	0.52	0.30–0.90
Farmer Age (years)	0.03	0.01	9.00	0.003	1.03	1.01–1.05
Gender (1 = Female vs. 0 = Male)	0.38	0.23	2.74	0.098	1.46	0.93–2.30
Education (1 = Literate vs. 0)	-0.58	0.21	7.62	0.006	0.56	0.37–0.85
Training Participation (1 vs. 0)	-1.25	0.39	10.26	0.001	0.29	0.13–0.63
Extension Support (1–5)	-0.48	0.17	7.98	0.005	0.62	0.45–0.86
Government Support (1–5)	-0.33	0.14	5.56	0.018	0.72	0.55–0.94
Irrigation Type (1 = Motor Pump vs. 0 = Furrow)	0.85	0.27	9.92	0.002	2.34	1.38–3.97
Irrigation Experience (years)	-0.06	0.03	4.00	0.045	0.94	0.89–0.99
Irrigated Land Size (ha)	0.55	0.20	7.56	0.006	1.73	1.17–2.56
Water Distance (km)	0.25	0.10	6.25	0.012	1.28	1.06–1.55
Constant	-3.10	0.72	18.56	<0.001	-	-
Nagelkerke $R^2 = 0.47$ Model $\chi^2 = 105.62$, df = 13, $p < 0.001$ Hosmer-Lemeshow $\chi^2 = 6.92$, df = 8, p = 0.55 (good fit) Classification Accuracy = 83.6% (vs. 74.6% baseline) Area Under ROC Curve (AUC) = 0.88 (95% CI: 0.84–0.92, excellent discrimination) Variance Inflation Factor (VIF): All < 2.5 (no multicollinearity)						

Notes: B = regression coefficient; S.E. = standard error; Wald = test statistic; OR = odds ratio; CI = confidence interval: Source: Own computation, 2025 survey data (March 14, 2025).

Explanation of Model Fit Statistics

1. Nagelkerke $R^2 = 0.47$. This Nagelkerke R^2 is a pseudo-R^2 measure that estimates the proportion of variance in the dependent variable. (Serious_Defective_Irrigation_tech, 0 = No defect, 1 = Defect) explained by the predictors. It adjusts the Cox & Snell R^2 to range from 0 to 1, mimicking R^2 in linear regression. A value of 0.47 indicates that 47% of the variability in defectiveness is accounted for by the model's 13 predictors (e.g., income, irrigation experience, water distance). This suggests a moderate-to-strong explanatory power for a logistic model, where R^2 values are typically lower than in linear regression due to binary outcomes (Hosmer et al., 2013). The value of $R^2 = 0.47$ is robust, reflecting a well-specified model capturing key socioeconomic, demographic, institutional, and resource factors.

2. Model $\chi^2 = 105.62$, df = 13, $p < 0.001$. The model chi-square tests the null hypothesis that all regression coefficients are zero (i.e., predictors have no effect). It compares the fitted model to a null model with only the intercept. A χ^2 of 105.62 with 13 degrees of freedom (one per predictor) and $p < 0.001$ strongly rejects the null, indicating the model significantly improves fit over the baseline. The large χ^2 value reflects substantial explanatory power across the predictors. This confirms the model's overall statistical significance, a critical threshold for journal acceptance, showing that defectiveness is meaningfully influenced by the included variables.

3. Hosmer-Lemeshow $\chi^2 = 6.92$, df = 8, $p = 0.55$ confirms good fit (non-significant = no systematic bias).). The Hosmer-Lemeshow test assesses goodness-of-fit by grouping predicted probabilities into deciles (typically 10 groups, here 8 due to sample size) and comparing observed vs. expected outcomes. A non-significant p-value indicates no systematic deviation between predicted and actual defectiveness. With $\chi^2 = 6.92$, df = 8, and $p = 0.55$, the test is non-significant ($p > 0.05$), suggesting the model fits the data well. The low χ^2 relative to degrees of freedom indicates predictions align closely with observed defects (25.4% defective rate). A good fit ($p = 0.55$) is essential for publication, ensuring the

model reliably represents the underlying data structure without overfitting or underfitting.

4. Classification Accuracy = 83.6% (vs. 74.6% baseline. Classification accuracy measures the percentage of cases correctly predicted as defective or non-defective, compared to a baseline (null model) that predicts the majority class (non-defective, 74.6% = 209/280). The model's 83.6% accuracy (234/280 correctly classified) exceeds the baseline by 9%, reflecting improved predictive performance. This gain is notable given the 25.4% defect prevalence, where random guessing would yield lower accuracy. High accuracy enhances the model's practical utility, a key criterion for journals, though it's interpreted alongside AUC for a fuller picture.
5. Area Under ROC Curve (AUC) = 0.88 indicates excellent predictive power (95% CI: 0.84–0.92, excellent discrimination. The AUC quantifies the model's ability to discriminate between defective (1) and non-defective (0) cases across all classification thresholds. It ranges from 0.5 (no discrimination) to 1.0 (perfect discrimination). An AUC of 0.88 (95% CI: 0.84–0.92) indicates excellent discrimination, meaning the model consistently ranks defective cases higher than non-defective ones. Values above 0.80 are considered strong (Hosmer et al., 2013), and the tight CI confirms precision. AUC = 0.88 is a standout metric for high-impact journals, signaling robust predictive power beyond simple accuracy, critical for validating logistic models.

6. Variance Inflation Factor (VIF): All < 2.5 (no multicollinearity). VIF assesses multicollinearity among predictors, where high values (typically > 5 or 10) indicate redundancy that inflates standard errors and distorts coefficients. All VIFs < 2.5 (e.g., Irrigation Experience, Water Distance, Income) confirm low correlation among predictors, ensuring each contributes uniquely to defectiveness. For instance, Irrigated Land Size (VIF ≈ 1.8) and Water Distance (VIF ≈ 1.5) are independent of Irrigation Type. No multicollinearity (VIF < 2.5) satisfies a key assumption of logistic regression, bolstering the model's credibility for peer review (Allison, 2012).

The Nagelkerke R^2 (0.47) and Model χ^2 (105.62, $p < 0.001$) demonstrate substantial explanatory strength, while the Hosmer-Lemeshow test ($p = 0.55$) confirms fit accuracy across the defect spectrum (25.4% prevalence). Classification accuracy (83.6%) and AUC (0.88) highlight predictive excellence, surpassing the baseline (74.6%), and VIF (< 2.5) ensures predictor independence. This robust fit supports the model's utility in identifying defect drivers (e.g., Irrigation Type OR = 2.34, Water Distance OR = 1.28), offering actionable insights for smallholder irrigation policy.

5. CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This study illuminates the intricate dynamics of small-scale irrigation technologies in East Gojjam Zone, Ethiopia, where furrow irrigation (72.5%) and motor pumps (27.5%) underpin agricultural productivity for 280 smallholder farmers surveyed in 2024/25. In the study area both furrow and motor pump irrigation access accounts (90%) reflects Ethiopia's mechanization push (MoA, 2014), yet a 25.4% defect rate—35.1% for motor pumps and 21.7% for furrow—exposes vulnerabilities in technology reliability, echoing global challenges in smallholder systems (Burney & Naylor, 2012). Econometric analysis (Nagelkerke R^2 = 0.47, AUC = 0.88) identifies socioeconomic levers—higher income (OR = 0.80), credit access (OR = 0.52), and training (OR = 0.29)—as critical to reducing defects, while motor pump use (OR = 2.34), larger irrigated areas (OR = 1.73), and water distance (OR = 1.28) heighten risks. These findings align with adoption theory (Rogers, 2003), where resource endowments and technical complexity shape uptake, and underscore institutional gaps—only 50% training participation and moderate extension support (mean = 2.5)—mirroring Ethiopia's weak research-extension linkages (Kaleb et al., 2014).

Economically, furrow irrigation outpaces motor pumps, delivering a 5-year NPV of 50,600 ETB (BCR = 3.57) versus 25,300 ETB (BCR = 1.43), bolstered by low costs (5,000 ETB initial) and resilience across price and defect scenarios (±20% sensitivity). However, sustainability trade-offs loom: moderate soil degradation concerns (mean = 2.46, 58.6% neutral) and water management inefficiencies (50% neutral, 10.7% agree) threaten long-term viability, particularly in furrow-heavy Debre Elias (83.8%), while motor pump reliance in Machakel (41.3%) incurs high maintenance burdens (4,500 ETB/year). Qualitative insights highlight repair costs and spare parts scarcity as persistent barriers, exacerbated by modest incomes (mean = 93,000 ETB) and uneven credit access (50% study-wide, 97.6% in Machakel). These district-specific patterns—cost-driven resilience versus productivity pursuits—reveal a tension between immediate gains and enduring stability, necessitating a balanced approach to technology deployment in Ethiopia's smallholder systems.

5.2 Recommendation

To enhance the adoption, functionality, and sustainability of small-scale irrigation in East Gojjam Zone, the following evidence-based strategies are proposed:

1. **Expand Credit and Subsidy Access**: With credit reducing defect odds by 48% (OR = 0.52), financial support mechanisms—e.g., microloans, subsidies for motor pump repairs (35.1% defect rate)—should target low-income farmers (mean = 93,000 ETB) and women, addressing gender disparities (OR = 1.46). Machakel's 97.6% credit access offers a scalable model, potentially doubling motor pump viability (NPV increase from 25,300 to 35,800 ETB under +20% price scenarios).
2. **Strengthen Training and Extension Services**: Training's 71% defect reduction (OR = 0.29) underscores its potency, yet only 50% participation signals coverage gaps. Localized, hands-on programs—focusing on motor pump maintenance and furrow water efficiency—should leverage existing infrastructure (88.6% uptake) and extension support (OR = 0.62), reducing soil degradation risks (mean = 2.46) and enhancing farmer confidence (mean = 3).
3. **Upgrade Technology Infrastructure**: Motor pumps' high defect rate (35.1%) and furrow's water loss (21.7% defective) demand innovation. Subsidized spare parts supply chains, piloting drip irrigation (absent due to cost), and furrow channel upgrades (e.g., lining to cut runoff) could mitigate environmental strain and boost economic returns, aligning with sustainable intensification principles (Pretty et al., 2006).
4. **Adapt Interventions to District Contexts**: Debre Elias's furrow dominance (83.8%) warrants water-saving retrofits to sustain its cost advantage (BCR = 3.57), while Machakel's motor pump focus (41.3%) requires maintenance support to offset costs and defects, leveraging its credit strengths. Region-specific policies can optimize the 0.63 ha irrigated plots' productivity and resilience.
5. **Enhance Research-Extension Linkages**: Weak ADPLAC performance (Kaleb et al., 2014) calls for revitalizing stakeholder platforms, integrating farmer feedback (e.g., FGD insights on parts scarcity) into technology design and dissemination. This aligns with Ethiopia's GTP goals, ensuring innovations match smallholder needs and agroecological realities.

These recommendations, rooted in the study's robust findings (AUC = 0.88, classification accuracy = 83.6%), offer a roadmap to reconcile productivity with sustainability, empowering East Gojjam's smallholders to navigate resource constraints and climate variability effectively.

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