

Technical efficiency of irrigated versus rain-fed wheat production among rural household farmers in East Gojjam Zone, Amhara Region, Ethiopia

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Abstract

Rural households across much of Sub-Saharan Africa continue to struggle with poverty reduction and food security, a challenge shaped by topography, climatic variability, demographic pressures, and socioeconomic conditions, while the continent's agricultural production still falls short of meeting food needs. Identifying technical efficiency levels and their determinants in both rain-fed and irrigated systems is therefore critical for policy design. This cross-sectional study of 420 households estimates the level of technical efficiency and identifies the determinants of inefficiency among irrigated and rain-fed wheat producers in the East Gojjam Zone, Amhara Region, Ethiopia, using the one-step Battese-Coelli stochastic frontier approach. Results show mean technical efficiency of 78% for irrigated wheat and 65.5% for rain-fed wheat, confirming that irrigated production is considerably more efficient, largely due to greater control over water management and crop husbandry. For irrigated wheat, land, seed, fertilizer, labor, and oxen significantly drove frontier output, while the household head's years of schooling, access to credit, extension contact, and total land owned significantly affected inefficiency. For rain-fed wheat, land, seed, fertilizer, and labor were significant output-driving inputs, while credit access, soil fertility, and distance to market significantly affected inefficiency. Under the noise variance heteroscedasticity model, distance to market and livestock asset value significantly influenced inefficiency. These findings point to substantial potential for raising wheat output using existing inputs in both systems. The government should therefore prioritize raising awareness of irrigation's efficiency advantages while strengthening institutional support and improving farmers' access to credit and extension services.

Introduction

Agriculture plays an essential role in food security and economic growth through sub-Saharan Africa, where smallholder farmers constitute the vast majority of producers (Nguyen-Anh et al., 2022; Nkamleu, 2004). Numerous studies have shown that despite the sector's pivotal role, systemic technical inefficiencies continue to constrain agricultural productivity, directly undermining regional efforts to achieve self-sufficiency in key food crops (Nano, 2023). In Ethiopia, this challenge is particularly acute although, agriculture serves as the cornerstone of the national economy contributing significantly to GDP and rural employment the sector is widely characterized by persistent low productivity stemming from subsistence-oriented farming, inadequate technology, and restricted input access (Getachew et al., 2020, p. 2; Mulusew & Hong, 2023).

This systemic constraint is unambiguously manifested in the wheat sub-sector. Wheat serves as a critical pillar of Ethiopian food security; however despite its strategic importance, domestic yields frequently fail to keep pace with the rapidly expanding national demand driven by urbanization and population growth (Ayenew et al., 2020, p. 10; Zegeye, 2020). Empirical evidence indicates that mean technical efficiency among wheat producers hovers around 0.77, reflecting a yield gap of approximately 659 kg/ha that could be closed through improved resource management (Tadele et al., 2018). Other assessments report that wheat yields frequently reach only 20 percent of their water limited potential with the majority of this shortfall attributed to technological deficits rather than suboptimal resource

allocation alone (Silva et al., 2021). Similarly, recent analysis of smallholder performance across wheat growing regions report technical efficiency score as low as 0.52 in specific zone (Fentie & Michael, 2025), while national- level estimates place average technical efficiency at approximately 0.66 (Kelemu & Negatu, 2016) a figure that collectively suggest substantial production gains remain achievable within existing technological constraint.

Beyond on-farm technical limitations, socio- economic and institutional barriers including high cost of agricultural inputs like fertilizers, improved seeds, limited access to modern agricultural machinery, and structural deficiencies in the provision of agricultural credit, and extension services remain primary obstacles preventing smallholder farmers from operating at the production frontier (Challa et al., 2026; Zegeye, 2020). The prevalence of subsistence base farming further compounds this inefficiencies widening the gap between domestic production and rapidly expanding national demand (Agazhi et al., 2024; Ayenew et al., 2020).

Recognizing this the Ethiopian government has promoted irrigated wheat expansion as a strategy for closing the national yield gap and bolstering food security (Ayenew et al., 2020; Senbeta & Worku, 2023b), positioning irrigation as a central pillar of the countries aspiration to emulate the productivity gains associated with “Asians Green Revolution” (Effa et al., 2023).

Despite this government initiative, a significant discrepancy exists between reported production surges and the countries continued reliance on commercial wheat imports to bridge the gap between domestic supply and demand (Ayenew et al., 2020; Senbeta & Worku, 2023b). This tension is starkly illustrated by conflict findings in the literature a persistence reliance on imports (Senbeta & Worku, 2023a) and others claim that the nation achieved total self-sufficiency in 2022 (Effa et al., 2023). This dichotomy between aspirational policy claims and the persistent reality of market dependent consumption underscores the urgent need for rigorous evidence-based scrutiny of agricultural efficiency at the micro level.

However, few studies have undertaken the micro level investigations needed to reconcile this conflicting macro-level narratives, little attention has been paid in particular to the comparative performance of irrigated vs rain-fed wheat systems and the socioeconomic and institutional especially on scheduling and financial liquidity challenges on farmers efficiency in their farm (Asmare et al., 2025; Fentie & Michael, 2025).

Although existing evidence from the Amhara region demonstrates household specific factors such as age, cultivated land size and irrigation involvement significantly influences technical, allocative and economic efficiency (Degfachew et al., 2025), their remains a scarcity of studies that effectively disaggregate this efficiency across the region diverse agro-ecological zones. This absence of micro-level disaggregated evidence makes it difficult to reconcile purported production successes with the persistent reality of household level food insecurity (Asfaw et al., 2019; Getachew et al., 2020).

A further methodological gap compounds this empirical shortfall. Most existing studies on wheat production efficiency in Ethiopia (Agazhi et al., 2024; Hailu, 2020) have relied on the conventional two-

step stochastic frontier analysis(SFA) which assumes that efficiency scores are observed without error and inefficiency determinants are independent of inputs used in the frontier and technical efficiency scores are first estimated from a frontier and subsequently regressed on hypothesized socio-economic and institutional determinants using a Tobit regression. But the assumptions of two step SFA frequently violated in practice(Battese & Coelli, 1995), and can produce inconsistent parameter estimates and unreliable statistical inference and raising question on the robustness of previously reported efficiency scores and inefficiency determinants. While two step studies dominate the literature, its limitation necessitates the use of one step in comparison with irrigated and rain-fed wheat production which is underutilized in the regio makes a statistically coherent and clear methodological and empirical gap in the study area.

To address this empirical and methodological gap, this study empirically evaluates the production efficiency of smallholder wheat farmers in East Gojjame Zone of Amhara region with two objectives (i) estimate the level of technical efficiency between irrigated and rain-fed wheat production (ii) identifying the socioeconomic and institutional factors like agricultural credit and extension contact affects inefficiency.

This study departs methodologically by employing one step SFA which jointly estimates the production frontier and inefficiency determinants within a single maximum likelihood framework. The framework is further extended through a heteroscedastic (vhet) specification in rain wheat production that allows the variance of the stochastic noise component to vary across farm households, providing a more robust and statistically coherent basis for identifying the determinants of technical inefficiency. This study contributes to the literature in three ways. First being the first in using a comparative and one-step BC stochastic frontier model with a heteroscedastic variance specification and more statistically robust estimates than the two-step approaches that dominate the existing literature. Second by using rainfed cultivation as an explicit control group against irrigated production as the treatment, it provides a rigorous comparative benchmark that disentangles irrigation-driven productivity gains from managerial and environmental confounds a comparison largely absent from prior micro-level research (Andualem, 2025; Effa et al., 2025). Third, by generating disaggregated, plot-level evidence from East Gojjam zone, the study helps reconcile the persistent disconnect between macro-level government claims of self-sufficiency and the field-level realities of production constraints and continued import dependency.

Literature Review

The agricultural sector serves as the cornerstone of food security across sub-Saharan Africa, where optimizing production efficiency is paramount to addressing the persistent prevalence of undernourishment(Habtu, 2024, p. 1). Wheat occupies a central role in this effort, serving as a primary staple crop whose domestic production is critical for stabilizing food availability across the continent, including Ethiopia(Sisha & Dillie, 2021, p. 2). However, current rain-fed wheat production systems often exhibit significant technical inefficiencies, largely driven by restricted access to improved inputs, climate-related shocks, and underdeveloped institutional support(Getachew et al., 2025; Hailelassie et al.,

2016). Socioeconomic and demographic variables, such as household size, educational attainment, and credit accessibility, remain critical determinants that dictate the extent of these productivity gaps among smallholder farmers(Enyew et al., 2022, p. 2).

In the Amhara region these inefficiencies are further compounded by limited institutional reach and uneven distribution of technological resources, which constrain farmers' ability to maximize their potential output(Degfachew et al., 2024). Consequently, this study addresses these challenges by employing Stochastic Frontier Analysis to quantify the technical efficiency levels of both rain-fed and irrigated wheat production systems in the region.

By providing a comparative assessment of these production modalities, the study offers a robust empirical foundation to guide policy interventions aimed at closing the yield gap and bolstering local food self-sufficiency(Mastewal Demil Kassa et al., 2019; Tiruneh et al., 2017). Ultimately, this research seeks to provide actionable insights for stakeholders to transition from subsistence-oriented farming toward high-output, efficient agricultural systems that can effectively mitigate the cycle of food insecurity in the Ethiopian highlands(Dessale, 2019b). By establishing a clear nexus between resource utilization and productivity outcomes, the study provides a critical framework for stakeholders to enhance agricultural resilience in the face of climatic and systemic challenges(Ayele & Tarekegn, 2021; Hailu, 2020). Specifically, this research aims to empirically estimate the technical efficiency of irrigated and rain-fed wheat production while identifying the specific socioeconomic, demographic, and institutional determinants that constrain optimal output levels. This dual-methodological framework provides a comprehensive evaluation of the performance disparities inherent in current smallholder practices, ultimately offering targeted policy recommendations to improve agricultural productivity(Assefa et al., 2025; Hussen & Tenaye, 2025). This study also provides micro level evidence on the level of efficiency on irrigated and rain feed wheat beyond political talks of the federal governments surplus production, bridging the critical disconnect between optimistic official aggregate reports and the persistent challenges of wheat import dependency and local food insecurity. Consequently, this research contributes to the literature by quantifying these performance discrepancies at the farm level, thereby exposing the systemic constraints that undermine the promise of irrigation-led agricultural transformation(Hunde, 2019). Building on this objective, the research addresses the critical need for micro-level data to evaluate whether irrigation adoption genuinely translates into household-level food availability or merely obscures underlying production bottlenecks(Degefu et al., 2025; Tilaye et al., 2023). By isolating these determinants, the study facilitates the development of evidence-based strategies to optimize resource allocation and improve agricultural outcomes within the region(Shikur, 2020; Sisay et al., 2015, p. 15). Additionally, irrigated wheat cultivation is a relatively new practice in the study area, and farmers' limited exposure to advanced agronomic techniques presents a unique opportunity to evaluate the extent and efficiency of irrigated wheat production compared to rain-fed wheat. This study will also help address existing gaps in knowledge and perceptions of irrigated wheat among scholars and relevant institutions.

Methodology

Description of study areas

East Gojjam Zone, one of the zonal administrations of the Amhara regional state, is located in the northwestern highlands of Ethiopia and is characterized by significant topographical and agro-ecological diversity, marked by natural landmarks such as the Abay River and Mount Choqa(Zemedu, 2018). The zone lies between 10°1'46" to 10°35'12" N latitude and 37°55'52" E longitude, with a landscape of mountains, valleys, and plateaus ranging from 1,500 to 3,577 meters above sea level, and mean temperatures of 7–15°C and 22–25°C. Its soils predominantly fertile black and brown soils alongside red soils underpin the zone's strong agricultural potential (Yizengaw et al., 2015). According to regional population projections, the zone's population reached an estimated 2.8 million in 2023, accounting for 15% of the regional population (BoDP, 2024). As in most of the Amhara region, the dominant livelihood is mixed crop-livestock farming (Alemneh et al., 2019). Strategically located about 305 km from Addis Ababa and 251 km from Bahir Dar, the zone serves as an important regional logistical and productive hub.

This study focuses on three purposefully selected woredas within East Gojjam Zone, chosen for their relative homogeneity in agro-ecological conditions and socio-economic profiles to ensure a consistent analytical framework. Mixed agriculture is the primary livelihood for rural households in these areas(Yizengaw et al., 2015), with teff, wheat, maize, and pulses as the dominant crops(EGZoA, 2020) .From the major crops grown in the study area wheat cultivation playing a pivotal role in both rain-fed and off-season production systems. Furthermore, livestock integration remains essential, functioning both as a core livelihood strategy and as a critical input for farming activities for crop production.

The figure below shows map of study area

Sample size

This study employed sample size formula developed by Cochran (1977) which is appropriate for surveys and researches when the study population is greater than 10000 and in study area the total rural households was 76247 and the sample size formula is stated below.

$$n_0 = \frac{z^2 p(1-p)}{e^2} \dots\dots\dots \text{Eq. 1}$$

where n_0 = is the required sample size

Z = Z-score corresponding to the desired level (95%, 1.96)

P = the estimated proportion of the population with the desired characteristics

e = Desired margin of error (± 5%, 0.05)

For maximum variability of the prevalence of irrigation, the researcher chose a prevalence of 0.5 probability. Thus, 384 is the minimum sample size for rural households. But due to the prevalence of current instability and active war a 10% non-response rate was added to the initial calculated sample. Additionally, a design effect of 5% was also added the initial sample size in the study area to adjust for the potential loss of precision associated with the sampling design employed which was a multi-stage sampling and common in situations where random access to individual households is constrained by insecurity, and individuals(sampling units) within the study area are more similar. Finally, the sample size becomes 441. But after data cleaning and removal of missing data and inappropriately filled questionnaires, the final sample size for this study becomes 420 (189 were adopters and 231 were non adopters).

Source of data

The sources of data for this study were across-sectional primary data collected in the year 2025 through questionnaire from rural households, interview with purposely selected Zonal and woreda level as well as kebele level agronomists, irrigation experts and crop development experts.

Sampling techniques

Sampling units for interview of farm households were selected using multi-stage sampling techniques. In the first stage East Gojjam zone was purposely selected because of its wheat producing potential. In the second stage three woreda administrative units (Baso Liben, Gozamen, and Debre Eliya) were purposely selected based on the irrigated wheat participants and potential and their similar topographic, environmental and socioeconomic makeup. In the third stage sample kebeles of irrigated wheat producing areas were purposely selected in consultation with woreda crop agriculture crop development experts. Similarly, adjoint rainy wheat producing areas were purposely selected. Finally, using systematic proportional random sampling techniques the participant rural households were selected for the study and sampling distribution is shown below in the table.

Table 1
Sample distributions

Selected Woreda Administration	Selected Kebeles on irrigated wheat adopters and proportions	Selected kebeles of non-adopters and proportions	Selected sample total household
Gozamne	Chertekel (43)	Libanose (38)	162
	Mayangetam (43)	Deneba (38)	
Baso-Liben	Yeduge (28)	Lemechen(38)	137
	Yegelaw(33)	Dogeme(38)	
Debre Eliyase	Yeguarate(21)	Yekegate (38)	121
	Yegedade(21)	Tija goter(41)	
Total	189	231	420

Method of data analysis

The data collected through interviewer-administered questionnaires were coded and edited using SPSS version 25, then imported into R version 4.6.1. The econometrics methodology employed was one-step Battese and Coelli (BC) stochastic frontier model. Additionally descriptive statistics like means, medians, and percentages were used to summarize the major socioeconomic variables and characterize the sample. Data from key informant interviews (KIIs) were analyzed using inductive thematic analysis and used concurrently with the quantitative analysis to triangulate findings and provide deeper contextual insight into the empirical results.

Stochastic frontier analysis

This study employs the one-step estimation procedure proposed by Battese and Coelli (1995), which jointly estimates the stochastic production frontier and the inefficiency effects model within a single maximum likelihood framework, ensuring theoretical consistency, minimizing estimation bias, and improving statistical efficiency (Coelli et al., 2005). This contrasts with the conventional two-step approach, which produces biased and inefficient parameter estimates (Wang & Schmidt, 2002) and is therefore less suited to obtaining robust, internally consistent estimates of both the production frontier and the determinants of technical inefficiency among rain-fed wheat-producing households. The study employs one-step BC-SFA model that mitigates the disproportionate influence of outliers on the estimated frontier and inefficiency effects, while preserving the theoretical consistency and single-stage estimation advantages of the standard Battese and Coelli (1995) framework. Rooted in the foundational work of Aigner, Lovell, and Schmidt, SFA offers a robust parametric framework for efficiency estimation (Constantin et al., 2009; Lee & Schmidt, 1993); (Kumbhakar & Lovell, 2003). By enabling formal statistical inference on both the production function parameters and the drivers of technical inefficiency and the

study used likelihood ratio test comparing the SFA result with the restricted model and to ensure that SFA efficiency estimates are statistically valid rather than merely descriptive, allowing researchers to reliably distinguish systematic managerial inefficiency from exogenous stochastic noise. Unlike OLS, which attributes all deviations from the estimated production function to random noise, SFA explicitly decomposes the composite error term into two distinct components: one capturing exogenous random shocks, such as weather or market fluctuations, and another capturing systematic technical inefficiency(Bakucs, 2011).

The study adopts the LDCS production function context, which recognizes that data points are not fully efficient and that inefficiency should be explicitly accounted for in estimating the production function; accordingly, the resulting composite error term makes the stochastic frontier model more analytically tractable than the conventional production function econometric model.

Mathematical one step BC stochastic frontier model

$$Y_i = \beta_0 + \beta_1 X_i + \nu_i - \mu_i \dots\dots\dots 2$$

Where ν_i = noise, μ_i =inefficiency and X_i are the exogenous factors (land, seeds, fertilizer, active labor and oxen were inputs affecting the frontier).

The technical inefficiency effect can be expressed as:

$$\mu_i = \alpha_0 + \sum_{j=1}^J \alpha_j z_{ij} + \omega_{ij} \dots\dots\dots 3$$

Where ω_{ij} is the stochastic noise, z_{ij} are the exogenous factors affecting winter wheat production, α are parameter estimates if α_j is negative that indicates a positive relationship between exogeneous factors and technical efficiency of wheat production and vice versa

The estimation techniques used in the study is a Maximum likelihood estimation technique in one step BC SFA with a truncated normal distributional assumption which is simultaneously estimating the frontier and inefficiency determinants and becomes unbiased. By adopting this simultaneous estimation technique, the study effectively avoids the potential biases inherent in two-stage procedures, ensuring that the determinants of inefficiency are integrated directly into the frontier model (Afio et al., 2018; Wadud & White, 2000)

Table 2
Variables, measurement and hypothesized expected signs

Variable	Definition and Measurement	Expected signs
Dependent variable		
<i>Wheat output in Kg</i>	Wheat yield produced in kg	
Independent variable		
<i>Sex</i>	Dummy if the HH is male headed 1, otherwise 0	+
<i>Education</i>	Years of schooling completed	+
<i>Farm experience</i>	Total irrigation and farm experience of w wheat producers in years	+
<i>Oxen</i>	Number of oxen power per day	+
<i>Agricultural Credit</i>	Access and availability of credit if the HH gets credit 1, otherwise 0	+
<i>Extension contacts</i>	Number of contacts with agricultural extension workers for the last six month	+
<i>Distance to market</i>	The walking minutes to the market	-
<i>Off/non-farm income</i>	Amount of non-farm income obtained in Birr	-
<i>Landholding size</i>	Total amount of landholding in hectares	+
<i>Seedlings</i>	Amount of improved seed use in kg for wheat irrigation	+
<i>Fertilizers</i>	Amount of fertilizer (DAP and Urea) in kg for wheat production	+
<i>Livestock holding</i>	Number of total livestock that a HH has and its current market value	+
<i>Age</i>	The current age of the household head in years	-+
<i>Household family size</i>	Total household family size in number	+
<i>Labor</i>	Household active labor per day	+

Results and discussion

Descriptive statistics

Table 3 draws on 420 rural households sampled from Gozamen, Debre Elias, and Baso Liben woredas in East Gojjam zone, comprising 189 irrigated wheat adopters and 231 rain-fed producers. The two groups

differ across several demographic, socioeconomic, and production dimensions.

Adopters were younger on average (42 vs. 49 years), consistent with younger farmers being more open to new technologies. They also had more schooling (4.67 vs. 3.60 years), suggesting education aids uptake of improved practices, and greater access to credit (68% vs. 56%), which likely eased input purchases. Household size was slightly larger among adopters (5.88 vs. 5.53), possibly easing labor constraints. Non-adopters reported more extension contact, yet this didn't translate into higher adoption—hinting that extension quality matters more than frequency. Adopters were also far more engaged in off-farm work (92.5% vs. 64%), which may have helped finance farm investment.

On farm resources, non-adopters had larger landholdings (0.76 vs. 0.45 ha), higher livestock value, and used more fertilizer (467 vs. 179 kg), seed (203 vs. 110 kg), and labor (3.39 vs. 2.34 labor-days). Adopters, however, used more oxen power (2.9 vs. 2.2 oxen-days), reflecting greater reliance on animal traction. Overall, despite smaller landholdings and lower input use, adopters' younger age, higher education, better credit access, and heavier oxen use point to more efficient resource use—suggesting household traits and resource access jointly shape adoption decisions and technical efficiency gaps between the two groups.

Table 3
Summary of descriptive statistics computed from own sources,2026

Variable	Number of observations (n = 189)	Number of observation (n = 231)
	Mean (S.D)	Mean (S.D)
<i>Age of household head(years)</i>	42(11.45)	49(8.79)
<i>Extension contacts for last 1year (dummy,1 = yes)</i>	69(0.46)	80.5(0.39)
<i>Household family size</i>	5.88(1.55)	5.53(1.34)
<i>Household heads Years of schooling</i>	4.67(3.72)	3.60(2.34)
<i>Agricultural credit (dummy,1 = yest)</i>	0.68(0.46)	0.56(0.49)
<i>Distance to market in minutes</i>	106(186.57)	78.15(43.75)
<i>Off farm activity (dummy,1 = yes)</i>	0.925(0.26)	0.64(0.47)
<i>Livestock asset value</i>	324689(148531)	369777(113034)
<i>Land use in hectare</i>	0.45(0.29)	0.76(0.42)
<i>active labor per day</i>	2.34(0.95)	3.39(1.22)
<i>Oxen per day</i>	2.9(0.92)	2.2(0.49)
<i>Fertilizer use in kg</i>	179(125)	467(249)
<i>Seed use in kg</i>	110(86.79)	203(154.13)
Source: Own computation (2026)		

Efficiency of irrigated wheat producers

Before the SFA, the study conducts a likelihood-ratio (LR) test which is used to assess whether the stochastic frontier model outperforms conventional OLS by testing $H_0: \gamma = 0$ (no inefficiency variance). The statistic, $LR = -2(\ln L(H_0) - \ln L(H_1))$, does not follow a standard chi-square distribution since H_0 lies on the parameter-space boundary; critical values were therefore drawn from (Kodde & Palm, 1986). Thus, for irrigated wheat, LR = 111.65 exceeded the 1% critical value (18.63, df = 7). For rain-fed wheat, LR = 160.54 (baseline, df = 7) and 203.10 (heteroscedasticity-corrected, df = 9) exceeded their respective critical values (18.63, 21.67). The null hypothesis is rejected in all cases, confirming that technical inefficiency is a statistically significant component of the error term and that the stochastic frontier model is the appropriate specification for analyzing technical efficiency in both production systems.

Table (4) below shows the coefficient of sigma ($\gamma = \sigma^2 u / \sigma^2$) is 0.5383 indicating that nearly 54% of the variation and the rest 46% of the variation is attributed to external shocks which is outside farmer's control.

The estimated mean technical efficiency of 78.3% suggests that, on average, irrigated wheat farmers produce approximately four-fifths of the potential output attainable under the existing technology and input levels. Consequently, there remains about 21.7% scope for increasing production through improved managerial efficiency without requiring additional production inputs. This finding demonstrates that efficiency improvement policies may generate substantial productivity gains even in the absence of technological change. On the other hand, the summation of the coefficients of input elasticities = $0.133 + 0.23 + 0.20 + 0.52 + 0.30 = 1.383$ confirming rejecting the null hypothesis of constant returns to scale and affirms increasing returns to scale implying that a 1% increase in the use of all inputs leads to an overall increment in irrigated winter wheat by greater than 1% which violates the assumptions of constant returns to scale.

The frontier estimation result founds *ceteris paribus*, a 1% change in the elasticity of the input variable land, seed, fertilizer (Dap and Urea), labor in days and oxen use in days leads to an increase in irrigated winter wheat output by a coefficient of (0.133, 0.23, 0.20, 0.52, and 0.30%) respectively and statistically significant at 1% level.

The findings are aligned with previous empirical works

Table 4
One step stochastic frontier for irrigated wheat

Variable	Frontier model	Inefficiency model (μ)
<i>Constant</i>	4.6282*** (0.2750)	-0.6840 (0.7399)
<i>ln(Land, winter wheat)</i>	0.1332*** (0.0390)	
<i>ln(Seed, irrigated wheat)</i>	0.2365*** (0.0454)	
<i>ln(Fertilizer, winter wheat)</i>	0.2096*** (0.0419)	
<i>ln(Labor active)</i>	0.5219*** (0.0638)	
<i>ln(Oxen use)</i>	0.3094*** (0.0907)	
<i>Irrigated wheat experience</i>		0.0263 (0.0649)
<i>Household family size</i>		-0.0111 (0.0241)
<i>Household head schooling</i>		-0.1039*** (0.0271)
<i>Agricultural credit(1 = yes)</i>		-0.1222** (0.0577)
<i>Extension contact(1 = yes)</i>		0.2196*** (0.0664)
<i>Total owned land</i>		0.2029*** (0.0769)
<i>ln(Livestock assets)</i>		0.0683 (0.0629)

Source: Own computation 20206: Notes: *** p < 0.01, ** p < 0.05, * p < 0.10. Standard errors in parentheses

<i>Variable</i>	<i>Frontier model</i>	<i>Inefficiency model (μ)</i>
<i>Gamma (γ)</i>	0.5383***	
<i>Lambda (λ)</i>	1.0799	
<i>σ^2u (inefficiency variance)</i>	0.0279*** (0.0104)	
<i>σ^2v (noise variance)</i>	0.0239*** (0.0058)	
<i>Log-likelihood</i>	35.1950	
<i>Mean technical efficiency</i>	0.783	
<i>Number of observations</i>	189	
Source: Own computation 20206: Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors in parentheses		

Determinants of irrigated wheat farmers inefficiency

Among the inefficiency variables household heads year of schooling and access to agricultural credit are statistically significant in affecting inefficiency at 1% and 5% level of significance with a δ coefficient = -0.1039 and - 0.122 significance respectively confirming that a one unit increase in the years of household heads schooling and access to agricultural credit leads to a decrease in inefficiency in irrigated winter wheat production by 0.1039 and 0.122 units respectively. The findings of education align with previous empirical works(Agazhi et al., 2024; Ayele & Tarekegn, 2022; Girma et al., 2024) .The result confirms that human capital theory which states that education improves managerial decision-making, enabling farmers to allocate resources more efficiently and adapt production practices(Huffman, 2001). Similarly access to agricultural credit solves liquidity cash constraints as a major barrier to efficient production. Credit enables farmers to purchase improved seed, fertilizer and other production inputs at the appropriate time rather than delaying investment because of financial shortages. KII discussions with experts also strengthen the finding by saying the season of irrigated wheat is a very difficult time for rural household farmers because the rainy season agricultural production is not yet collected and marketed and rural household farmers at that time faces shortage of cash and the prevalence and availability of credit is a significant factor for irrigated wheat production activity through enabling timely input purchases which improves the efficiency of the production process. In the study area the coefficient of extension contact unexpectedly increases technical inefficiency and statistically significant ($\delta = 0.2196$, $p < 0.01$) which is against conventional extension theory which states that extension services improve managerial ability and production efficiency. Previous empirical finding (Agazhi et al., 2024; Ayele & Tarekegn, 2022; Girma et al., 2024) were against the findings of this study.

The positive association between extension contact and technical inefficiency might reflects the disruption of agricultural extension services resulting from prolonged conflict in the study area because

KII discussions with all woreda and zonal administration units responded on the support of extension service on irrigated wheat production program saying “conflicts for the last three years and which continued up to the present makes the institutional support service inactive and cannot be reachable and we cannot say that there is proper extension support in zonal administration units at all levels and the frequency, quality, and effective support of extension services were substantially reduced during the conflict and even within the last one year”

The findings of KII and empirical findings also aligns with agricultural extension theory because effective extension requires regular interaction and demonstrations at field level as well as follow up visits and timely technical advice at farm level but in the study area development agents were unable to provide regular farm visits, technical supervision, and training because of insecurity. Additionally, the study explores the contacts of development agents rather than the quality of the services and supports provided by extension services.

In addition, all of the respondents of KII replied by saying there is problem in institutional arrangement on the irrigation extension service and there is no independent position which supports the wheat irrigation development and the yearly crop production development agents try to support but it is ineffective because even the extension development experts are new to the activity and not well trained.

KIIs with East Gojjame zonal agricultural office extension communication expert' states the situation by saying *“The prevalence of armed struggle in our area makes the agricultural extension service support ineffective for the last three years and the problem is as you have seen it in your visit and movement across woredas and the time is very difficult and everybody thinks about survival rather than supporting rural household farmers and most report contact for the purpose of salary”*. And Another agronomist from zonal agriculture office explains the supports of extension service by saying *“most of our development extension service experts leave their work area because of the prevalence of armed conflicts for the last three years and almost we can say that there is disruption on the support and follow of extension services and rural household farmers are recently coming to our office to ask assistance and support because extension service experts cannot go to rural household farmers work area”*.

On the other hand, total amount of land owned in hectare is positively affects inefficiency with a coefficient and p-value of ($\delta = 0.2029$, $p < 0.01$) implying that although those households who have large farms generally possess greater resource endowments, management theory suggests that increasing operational scale also increases managerial complexity. The findings are also aligned with previous

Table 5
One step base and robust heteroscedastic SFA for rain-fed wheat producers

Variable	Baseline Coef.	Robustness Coef.
<i>Constant</i>	6.170*** (0.491)	6.005*** (0.380)
<i>ln(land for rainy wheat)</i>	0.163** (0.076)	0.375*** (0.067)
<i>ln (seed quantity)</i>	0.056 (0.038)	0.076*** (0.023)
<i>ln (fertilizer quantity)</i>	0.225** (0.089)	0.288*** (0.069)
<i>Ln(labor)</i>	0.396*** (0.068)	0.151** (0.063)
<i>ln(oxen use)</i>	0.139 (0.103)	0.053 (0.066)
Inefficiency model		
<i>Constant</i>	-0.684 (1.577)	-2.452 (1.983)
<i>Household heads Schooling</i>	-0.022 (0.016)	-0.004 (0.021)
<i>Distance to market</i>	0.006*** (0.001)	0.005*** (0.001)
<i>Soil fertility medi(ref.=low)</i>	-0.409*** (0.099)	-0.512*** (0.121)
<i>Soil fertility, good(ref.=low)</i>	-1.735*** (0.376)	-8.912 (7.564)
<i>Farm Experience</i>	-0.006 (0.004)	0.002 (0.005)
Source: Own computation 2026		
Note: Standard errors in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% levels.		

Variable	Baseline Coef.	Robustness Coef.
<i>Access to credit</i> (1 = yes)	-0.289*** (0.069)	-0.355*** (0.088)
<i>Ln(livestock assets)</i>	0.127 (0.123)	0.240 (0.154)
<i>Loglikelihood</i>	-22.762	-1.485
<i>Gamma (γ)</i>	0.927	0.725
<i>Lambda</i> (λ)	3.568	1.622
<i>Mean TE</i>	0.576	0.656
<i>ln(σ_u^2)</i>	-2.077*** (0.157)	-2.085*** (0.185)
<i>ln(σ_v^2)</i>	-4.621*** (0.289)	24.665*** (6.320)
<i>Number of observations</i>	231	231
The noise variance heteroscedasticity (vh_{et}) robustness model		
<i>Distance to market</i>		0.025*** (0.004)
<i>Ln(livestock assets)</i>		-2.394*** (0.490)
Source: Own computation 2026		
Note: Standard errors in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% levels.		

Rain-fed wheat production one step SFA

The results of the one-step Battese and Coelli (BC) robust stochastic frontier analysis (SFA) model for the rain-fed wheat production frontier reveal that land, improved seed, and chemical fertilizer (DAP and urea) exert positive and statistically significant effects on wheat output among rural farming households in the study area. Specifically, the estimated output elasticities for land, improved seed, and fertilizer are 0.375, 0.076, 0.288, and the coefficients were significant at the 1% level respectively, indicating that 1% increase the inputs is associated with corresponding increases in rain-fed wheat production of approximately 0.375%, 0.076%, and 0.288% respectively. Whereas labor is positive and statistically significant at the 5% level suggesting that, ceteris paribus, a 1% increase in daily active labor input is associated with a 0.151% increase in rain-fed wheat production. Others like (Biru, 2019) found that labor

is negative and insignificant. The above result aligns with (Chiarella et al., 2023; Daum, 2023; Girma et al., 2024). By contrast, although the coefficient for oxen use is positive, it fails to attain statistical significance, indicating that oxen power does not exert a measurable influence on rain-fed wheat production in the study area. This result diverges from that observed in the irrigated wheat production frontier, where oxen use was found to play a significant role in enhancing output. The findings are also align with previous findings (Dessale, 2019a) found that improved seeds and fertilizers were positive and significant determinants. Similar

The estimated mean technical efficiency derived from the robust model is 0.656, compared with 0.576 obtained from the baseline SFA model. This improvement suggests that the robust specification offers a more accurate representation of the underlying production process by mitigating the influence of outliers and enhancing the precision of technical efficiency estimates. This upward revision suggests that the robust specification offers a more accurate representation of the underlying production process by mitigating the influence of outliers and enhancing the precision of technical efficiency estimates. The resulting efficiency level implies that, on average, rain-fed wheat farmers in the study area could increase output by approximately 34.4% using existing technology and resource endowments, a gap broadly comparable to inefficiency levels reported in similar smallholder cereal production contexts. The mean TE findings nearly align with previous researches 82%, 62%, 76.9%, (Dessale, 2019a; Hailu, 2020; Tadele et al., 2018) respectively

Determinants of rain-fed wheat production inefficiency

As Table 5 shows, distance to market raises inefficiency significantly (1% level) in the wheat model: a 1% increase in distance to the nearest market raises technical inefficiency in rain-fed wheat by 0.005%. This reflects the practical constraints of remote farmers, who face delays in accessing inputs and difficulty marketing surplus output.

For soil fertility (poor, medium, good), medium-fertility land is significantly linked to lower inefficiency (1% level) versus poor-fertility land, showing that better soil substantially boosts efficiency. Good fertility, however, is only marginally significant (5%) in the base model and loses significance in the robust one suggesting few farmers actually have high-fertility land. This matches KII evidence from agricultural experts, who noted severe soil salinity in the zone that makes wheat cultivation largely unviable without fertilizer, consistent with (Girma et al., 2024). Experts recommended prioritizing organic fertilizers and calcium carbonate amendments to address salinity.

Access to credit also significantly reduces inefficiency (1% level) in both the base and robust models: a 1% rise in credit access lowers technical inefficiency among rain-fed wheat farmers. The findings were supported by previous works of (Dessale, 2019a; Mamo et al., 2018) who highlight credit's role in helping farmers adopt productivity enhancing inputs and practices. Whereas Livestock asset value, schooling, and farm experience, however, were not significant determinants of inefficiency showing positive, negative, and positive signs, respectively.

As further shown in Table 5, the noise variance heteroscedasticity (vhet) variables (distance to market and livestock asset market value) were found to significantly influence the variability of the rain-fed wheat production frontier. Distance to market is positively associated with inefficiency and statistically significant at the 1% level, implying that, ceteris paribus, each additional unit of distance from the market increases mean technical inefficiency by 0.005 units. This result again reflects the tangible disadvantages confronted by farmers situated farther from key agricultural markets. Conversely, livestock asset market value is negatively associated with inefficiency in the vhet model, such that a 1% increase in household livestock assets corresponds to a 2.394% reduction in the variability of the random noise component of the stochastic frontier. This finding suggests that greater livestock asset holdings are associated with reduced unexplained production shocks, thereby contributing to a more stable and predictable production environment.

Conclusion and recommendation.

For a country such as Ethiopia, which continues to strive for food self-sufficiency and poverty alleviation through the expansion of wheat irrigation as a national strategy, understanding the level of efficiency and inefficiency across irrigated and rain-fed wheat production is critical. This study employed the one-step SFA model for irrigated wheat and a robust noise-variance heteroscedasticity SFA (Vhet) model for rain-fed wheat production to estimate technical efficiency and its determinants. The results show an average technical efficiency (TE) of 78% for irrigated wheat compared to 65.5% for rain-fed wheat, demonstrating those irrigated producers achieved substantially higher efficiency and underscoring the critical role of management practices particularly water use in enhancing productivity. Correspondingly, considerable potential remains to raise output without additional inputs or technological change: 21.7% for irrigated and 34.5% for rain-fed wheat production. Among irrigated wheat producers, years of schooling and access to agricultural credit significantly reduced inefficiency, whereas extension contact and total landholding significantly increased it the former reflecting weaknesses in institutional extension support, the latter suggesting that larger landholdings pose greater management challenges. For rain-fed wheat production, distance to market, soil fertility, and access to agricultural credit were significant determinants of inefficiency, while the robust Vhet model further confirmed that distance to market and livestock ownership significantly influenced efficiency operating through reduced transaction costs and enhanced resilience and input access, respectively.

To improve productivity in both irrigated and rain-fed wheat production systems and advance national food self-sufficiency goals, it is essential to strengthen the quality and independence of institutional extension services, particularly in support of irrigation scheme management, while simultaneously addressing farmers' financial liquidity constraints through expanded access to agricultural credit with particular attention to rain-fed wheat-producing households, who face compounding structural disadvantages relative to their irrigated counterparts.

Declarations

Declaration of Informed Consent

Informed consent was obtained from participants during data collection

Consent to participate:

Informed consent was obtained from all respondents participating in both the questionnaire survey and key informant interviews (KIIs) and verbal informed consent was obtained from each participant before data collection, and all responses were treated confidentially and used solely for research purposes.

Consent to publish:

Not applicable. The study does not include any identifiable images or personal information

Declaration of Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Clinical trial number

not applicable in this study

Ethics approval:

The study protocol was approved by Woldia university college of business and economics IRB committee with Ref: WDU/IRB/050/2026 in accordance with Woldia university ethical standards and the IRB committee fully confirms that the study was conducted with the national and institutional ethical guidelines of woldia university.

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Author Contribution

All authors contributed to the conception and design of the study in the proposal development, data collection and analysis and manuscript write-up and editing.

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Data Availability

The data is available from the authors upon reasonable request

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Figures

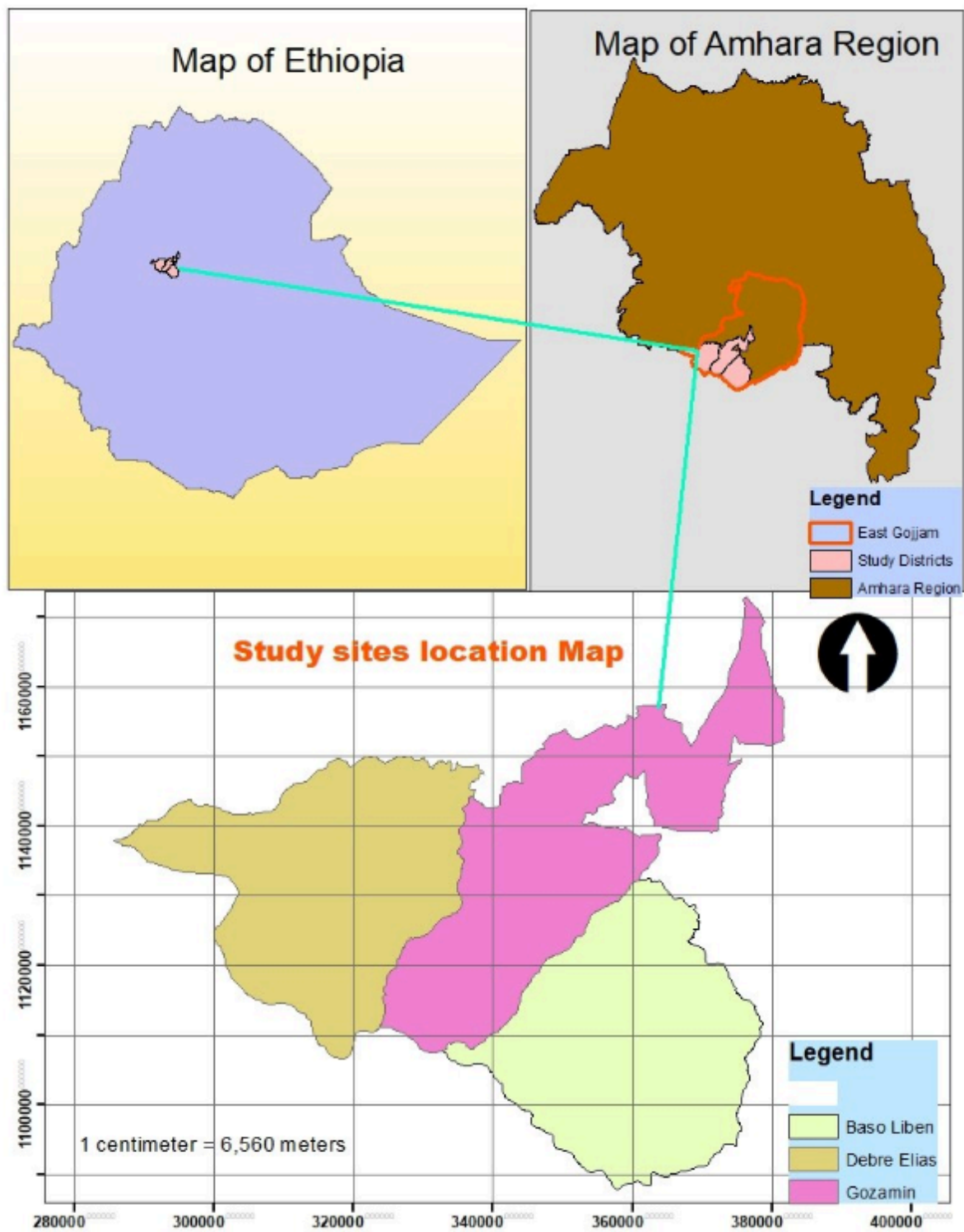


Figure 1

Map of study area: Source own construction (2025)