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Unlocking Agricultural Efficiency: A Stochastic Frontier Analysis of Smallholder Farmers in Rwanda

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CONTENTS

TABLES

FIGURES

ABSTRACT

Agriculture is central to Rwanda's economy, supporting the livelihood of about 70% of the population and contributing significantly to GDP. Smallholder farmers face many production challenges such as limited use of modern inputs, low productivity, and vulnerability to climate change. Despite efforts like the Crop Intensification Program and the Smart Nkunganire System, which aim to enhance access to resources, agricultural productivity remains suboptimal for Rwanda smallholder farmers. This study seeks to identify specific sources of technical inefficiencies among smallholder farmers, focusing on the total value of farmer's crop output. By using stochastic frontier analysis, a robust quantitative method for separating inefficiencies and random shocks, the study assessed the overall technical efficiency of smallholder farmers in Rwanda and identified the key factors influencing crop output value. The analysis reveals that fertilizer use, pesticide application, labor, seed use, and land size are key drivers of crop output value. This research further indicates that farmers operate at only 45% of their potential productivity, given the same level of input and technology, highlighting substantial room for efficiency improvements to reach the optimal output value frontier. Furthermore, additional analysis emphasizes the critical role of socioeconomic factors in shaping technical efficiency. The findings highlight the need for targeted interventions to optimize resource utilization, streamline labor allocation and strengthen access to extension services and government initiatives aimed at boosting agricultural production value. These strategies can substantially improve technical efficiency, enabling farmers to achieve optimal crop output values and advancing Rwanda's agricultural development objectives.

1. INTRODUCTION

Agriculture is a pivotal sector in Rwanda, serving as the primary source of livelihood for approximately 70% of the population, and contributing significantly to the country's GDP (World Bank, 2020). Furthermore, a recent government census highlights the pivotal role of agriculture in the country's economy, with 53.4% of the employed population engaged in agriculture activities, solidifying it as the dominant economic sector (NISR, 2022). Smallholder farmers, who form the backbone of the sector, face numerous challenges, including limited access to modern agricultural inputs, insufficient extension services and increasing vulnerability to climatic change. In response, the Rwandan government has implemented a series of strategic initiatives, such as the Crop Intensification Program (CIP) and the Smart Nkunganire System (SNS). These programs focus on increasing land use efficiency, improving access to seeds, fertilizers, and extension services, and strengthening food security. The goals of these interventions align with the broader objectives of the previous PSTA 4 framework, while PSTA 5 will build on its achievements to drive further progress. However, despite these efforts, agricultural productivity remains suboptimal, with many smallholder farmers unable to fully capitalize on the available resources (MINECOFIN, 2020). Addressing these persistent challenges requires a deeper understanding of the factors influencing agricultural efficiency, particularly technical efficiency,[1] which reflects how effectively farmers convert input into outputs and subsequently translate those outputs into monetary value.

The Food and Agriculture Organization (FAO) (2020) emphasizes the importance of measuring agricultural efficiency to inform policy development and foster sustainable agricultural practices. Previous studies conducted in Rwanda have also demonstrated that improving technical efficiency can lead to significant gains in agricultural output without the need for additional inputs, which is crucial in resource-constrained environments like Rwanda (Ngango and Hong, 2021; Ubarijoro et al., 2016). For instance, Bizimana et al. (2018) assessed the technical efficiency of maize farmers and identified inefficiencies largely driven by inadequate access to inputs and extension services. Similarly, Kanyamibwa et al. (2021) highlighted the role of farm management practices and financial resource access in determining technical efficiency in coffee production. Other studies, such as Ubarijoro et al. (2016), have shown the positive impact of technologies like improved seeds and organic fertilizers on agricultural production.

While previous studies in Rwanda have provided valuable insights into the technical efficiency of single-crop outputs, they often overlook the broader efficiency dynamics of smallholder farmers managing diverse crops. This shortcoming limits our understanding of how smallholders optimize resources to maximize economic returns across their entire crop portfolio. This study addresses this by analyzing technical efficiency among smallholder farmers, focusing on the conversion of key inputs—land, labor, seeds, fertilizers, and pesticides—into optimal monetary returns from all household crop outputs. In addition, this research examines the role of socioeconomic factors, including household and farm characteristics, environmental conditions, and participation in agricultural initiatives, in shaping efficiency outcomes. By offering a holistic value perspective, the findings deliver actionable insights to optimize resource allocation and maximize the economic value of crop production among smallholder farmers in Rwanda.

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[1] When using crop output value as the point of analysis, technical efficiency refers to the ability of a farmer to maximize the value of crop production from the resources (inputs) they use, given the best available technology or production frontier. In this context, it measures how well a smallholder farmer converts inputs—such as land, labor, seeds, fertilizers, and pesticides—into the highest possible monetary value of crops, compared to the most efficient producers in the sample.

2. METHODS AND DATA

2.1 The stochastic frontier Analysis

Stochastic frontier analysis (SFA)[2] is a widely adopted methodology for evaluating production efficiency, particularly in agricultural systems. This model decomposes the unexplained aspect of the production function into two components: one capturing inefficiency in production, and the other capturing the random noise or statistical error - often due to measurement errors or external shocks (Battese & Coelli 1995, Aigner et al. 1977). Originally introduced by Aigner et al. (1977) and later refined by Meeusen and van den Broeck (1997), SFA assumes firms often operate below their potential due to inherent inefficiencies that need to be separated from stochastic error. This study estimates the technical efficiency of Rwanda smallholder farmers by analyzing how well they convert inputs into monetized crop outputs under given resource and structural constraints. To ensure comparability across diverse crops, physical quantities have been converted into a standardized monetary metric, enabling the aggregation of all household crop production into a single measure of total crop output value. Such an approach provides a unified framework for analyzing production efficiency and economic outcomes.

In a scenario with multiple inputs contributing to a single monetary-valued output. The general form of the stochastic frontier production function is given by:

$Y_i = f(X_i; \beta) + \varepsilon_i, \ldots$ (1)

Where Y_i represents the total value of crop output for the i^{th} household, calculated by summing the monetary values of all crops produced in the i^{th} household. This is done by multiplying the quantity of each crop produced by the household with its price and then adding these values together.

X_i is the vector of input variables for the i^{th} household; β is the vector of parameters to be estimated; $f(X_i; \beta)$ represents the production function for the i^{th} household (e.g., Cobb-Douglas, translog); and ε_i is the error term, capturing random inefficiencies and unobserved factors. The error term can also be further decomposed into:

$\varepsilon_i = \nu_i - u_i \;\ldots$ (2)

where, ν_i is the random error term assumed to be normally distributed with zero mean and constant variance, $N(0, \sigma_v^2)$ and u_i represents a non-negative inefficiency term, representing the deviation from the frontier (inefficiency), which is assumed to follow a half-normal, exponential, or truncated normal distribution with variance σ_u^2 (Coelli et al., 2005). This approach was initially developed by Aigner et al. (1977), who provided a foundation for analyzing production efficiency by differentiating between random shocks and inefficiency effects.

The study specified the stochastic frontier model using a translog production function with input variables. The translog function is preferred over Cobb-Douglas due to its flexibility in capturing complex, non-linear relationships between inputs, such as labor, fertilizer, and land, which may interact in variable elasticities and interaction terms, an essential feature in agricultural production. The translog model enables us to better reflect these complexities and variations in production processes, providing a more accurate analysis of technical efficiency (Kumbhakar and Lovell, 2000; Christensen, Jorgenson, and Lau, 1973).

[2] Stochastic frontier analysis is an econometric method used to measure the efficiency of production. In this study, it measures efficiency by estimating the maximum achievable crop value output value from given inputs.

Additionally, we assume a half-normal distribution for the inefficiency term due to its simplicity, ease of estimation, and widespread use in the literature (e.g., Aigner et al. 1977, Meeusen and van den Broeck 1977, and Greene 2008). This choice ensures non-negative inefficiency, making it a robust and interpretable assumption for our analysis.

The translog production function includes both linear and interaction terms to account for the relationships between inputs (X_i) and their joint influence on the output value (Y_i) .

The translog model is specified as follows:

$$lnY_i = \beta_0 + \sum_{i=1}^{n} \beta_i \, lnX_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \gamma_{ij} \, ln \; X_i \, ln \; X_{ij} + (v_i - u_i) \ldots \text{(3)}$$

Where Y_i is the value of total crop output of the individual farm household; X_i represents input variables, such as land size, labor cost, fertilizer and pesticide, and seed cost; β_0 is the intercept; β_i are the coefficients corresponding to the input variables; γ_{ij} represents the parameters for the interaction terms, capturing how different input variables jointly influence the output value; and $v_i - u_i$ is the inefficiency term.

After estimating the model, technical efficiency (TE_i) is calculated for each observation by computing the inefficiency term u_i. Therefore, the TE for each observation is calculated as:

$$TE_i = \frac{Y_i}{Y_i^*} = \frac{Y_i}{f(X_i;\beta) \; exp\,(v_i)} = \; exp\,(-\,u_i) \ldots \text{(4)}$$

Y_i is the actual output, valued in monetary terms, for each farmer, and Y_i^* is the maximum possible output value based on the estimated production value frontier, $f(X_i, \beta)$ is the predicted output value from the translog production function. u_i represent the inefficiency for the ith farmer. If $u_i = 0$,the farmer is perfectly efficient (i.e., they operate on the efficiency frontier), and if $u_i > 0$, they are technically inefficient.

The estimated TE scores for each farmer represent how efficiently they use their resources (inputs) compared to the highest possible monetary outcome (frontier). The value of TE ranges from zero to one, where a TE equal to one indicates that the farmer exhibits perfect efficiency and is operating on the production value frontier.

A TE less than one indicates inefficiency, with smaller values reflecting less efficiency. A farmer with higher technical efficiency is closer to the production value frontier, while those with lower scores are more inefficient (Aigner et al., 1977, Battese & Coelli, 1995).

Using Stochastic Frontier Analysis (SFA), with a translog production function, provides quantitative estimates of technical efficiency and input elasticity, as well as input use efficiency and as well as potential drivers to improve agricultural output value in Rwanda.

2.2 Tobit Model

In this study a Tobit Model[3] was utilized to analyze the effect of various socioeconomic factors on technical efficiency, because the efficiency scores are censored or truncated (Tobin, 1958). Since the TE scores are between zero and one (i.e., they cannot be negative nor exceed 100 percent efficiency), the Tobit model is appropriate for handling the specific distribution of the dependent variable. This model estimates the factors of various socioeconomic factors on the TE of farm production. These factors include household size, age and gender of the household head, access to extension services, and participation in agricultural programs.

The Tobit model is specified as:

$$TE_i^* = \beta' X_i + \varepsilon_i \ldots (5)$$

TE_i^* is the latent variable representing the potential technical efficiency, X_i denotes the vector of explanatory variables (socioeconomic factors) for the i^{th} observation, β' represents the parameters to be estimated that is a vector of coefficients corresponding to the explanatory variables, and ε_i is the error term assumed to be normally distributed $N\,(0, \sigma_v^2)$. The observed technical efficiency TE_i is censored between zero and one, reflecting the minimum and maximum bounds of efficiency scores.

The observed TE score is defined as:

$$TE_i = \begin{cases} TE_i^* & if\ 0 \leq TE_i^* \leq 1 \\ 1 & if\ \ TE_i^* \geq 1 \\ 0 & if\ \ TE_i^* \leq 0 \end{cases} \quad \ldots..\ (6)$$

Tobit model results intend to provide insights into the factors influencing farmers' technical efficiency, providing insights to guide policy recommendations for maximizing smallholder crop output value.

2.3 Data

This study leveraged data from the Smallholder Commercialization Survey, building on the work of Warner et al. (2023) and other key studies that have examined crop commercialization (Warner et al., 2024), farm typologies (Benimana et al., 2024), and the costs and returns in Rwandan smallholder agricultural production (Mugabo et al., 2024).

The stochastic frontier analysis (SFA) framework, used to measure technical efficiency, incorporates total crop output valued in monetary terms. The approach standardizes and aggregates diverse crops, addressing the challenge of comparing physical quantities (e.g., 1 kg of maize vs. 1 kg of Irish potatoes), which differ in characteristics and market value. By valuing output in monetary terms, we create a unified, comparable measure of production efficiency across various crops and regional prices.

[3] The Tobit model is a censored regression model used when the dependent variable is continuous but limited within a range. In this case efficiency scores are bounded between 0 and 1. Tobit helps analyze relationships while accounting for these limits, making it ideal for data with natural cutoffs.

The data used also encompasses key agricultural inputs such as land, measured in hectares, labor, fertilizers, seeds, and pesticides represented in monetary terms to reflect their associated amount used. This approach not only reflects the economic investment involved in crop production but also offers a more comprehensive view of resource allocation across different types of inputs. Building on the methodologies of Latruffe (2017), Bonfiglio (2019), and Tenaye (2020), crop outputs and inputs are measured in monetary terms to enable consistent comparisons. To further enhance accuracy, these values are adjusted for regional price variations and seasonal fluctuations, ensuring they represent local market dynamics and conditions accurately across various production environments. This framework thus provides a robust basis for assessing efficiency while accounting for localized economic factors that influence agricultural productivity.

The Tobit model analysis integrates diverse data sources to capture the effect of household, programmatic, and farm-specific factors on technical efficiency. This approach provides a deeper understanding of how household demographics, access to agricultural programs, and farm attributes contribute to efficiency variations. Household factors, including gender, age, literacy, size of the household head, and access to wage income, are considered social dynamics influencing efficiency. Programmatic factors, such as access to extension services, the Smart Nkunganire System, farmer field schools, participation in cooperatives, and land-use consolidation programs, are hypothesized to improve resource use, knowledge transfer, and market access, thereby enhancing efficiency. Farm characteristics, like livestock production, monocropping, land ownership, altitude, rainfall variability, and market proximity, account for environmental and logistical challenges affecting performance. This comprehensive analysis illustrates how social, economic, and environmental factors interact to maximize smallholder farmer agricultural output value.

The selection of these variables is grounded in established literature, including studies on technical efficiency and factors affecting it across different regions and crops in Rwanda, as seen in the works of Ngango and Hong (2021), Ubarijoro et al. (2016), Bizimana et al. (2018), Tenaye (2020), and Bonfiglio et al. (2020). Furthermore, these variables align with key indicators and objectives outlined in Rwanda's Fourth Strategic Plan for Agricultural Transformation (PSTA 4), supporting the development of evidence-based policies and strategic initiatives aimed at driving agricultural transformation in Rwanda. This alignment is intended to address essential areas of growth, efficiency, and sustainability within the sector.

3. RESULTS AND DISCUSSION

3.1 Descriptive statistics of variables

On average, each household cultivates an average of four different crops across its plots during the 2021–2022 agricultural year. This study aggregates the total crop production per household by calculating the total output value of all cultivated crops. Staple crops, including bananas, maize, cassava, sweet and Irish potatoes, and beans, constitute a significant portion of household production. In addition, farmers often grow fruits and vegetables, with avocados and tomatoes being prominent, though they are cultivated less frequently, they are typically grown for commercial purposes. Irish potatoes, maize, and cassava serve both consumption and commercial needs. In contrast, beans, sweet potatoes, and bananas are mainly cultivated for household consumption, highlighting their importance as subsistence crops. In Rwanda, monocropping is the dominant agricultural practice, followed by mixed cropping, as noted by Warner et al. (2023).

Based on the variables[4] used in this study, the average total crop output value per household was 190.6 USD, highlighting the economic contribution of smallholder farming. The primary inputs examined include land and it is the basic asset of smallholder farmers in Rwanda with each household cultivating an average of 0.4 hectares, underscoring the small-scale nature of Rwandan agriculture. Households spent an average of 10 USD on seeds and 33 USD on fertilizers, pesticides, and fungicides. While 48.5% of households used inorganic fertilizers and 83.2% used organic fertilizers, only 16.4% applied pesticides or fungicides. These inputs are vital for enhancing crop output, increasing farm income, and ensuring food security, which is why the Rwandan government supports their use through subsidies, particularly for improved seeds and inorganic fertilizers, in line with the Strategic Plan for Agricultural Transformation (PSTA) policy frameworks.

Fertilizers make up the largest portion of the input subsidy budget and are the most significant cash expense for farmers (Spielman et al., 2022). Labor is also a significant production input, with households spending an average of 33.3 USD on labor. This expenditure highlights the importance of labor in smallholder farming, where manual work is essential to maintain and cultivate the land effectively. Overall, this analysis offers a detailed overview of these inputs that shape household crop production values efficiency in Rwanda.

Factors hypothesized to influence farmers' technical efficiency in crop production are listed in Table 5. For a detailed description of these variables, refer to the Rwanda Smallholder Commercialization Survey Overview, which offers comprehensive insights into each selected variable.

3.2 Key drivers of crop output using stochastic frontier analysis

Table 1 provides maximum likelihood (ML) estimates for translog production functions, identifying key drivers of crop output value among Rwandan smallholder farmers. This study shifts the focus from crop quantity to examine crop output value, providing critical insights for policymakers in Rwanda aiming to help smallholder farmers go beyond simply producing a higher quantity of crops and focuses on how effectively they can turn their inputs into the highest possible monetary value of crop output. The findings highlight opportunities to boost crop production, emphasizing land size, seeds, labor, fertilizers, and pesticides as key inputs.

The results show a significant positive impact of fertilizers and pesticides on crop output value, emphasizing their crucial role in boosting economic returns for smallholder farmers in Rwanda. This finding aligns with research by Ngango and Hong (2021), who observed that inorganic fertilizers significantly increased maize production in Rwanda and is further supported by REMA (2016) and Muriithi et al. (2022), who also found that improved agricultural inputs, including fertilizers and pesticides, substantially boost crop value outputs. For smallholder farmers in less mechanized systems, effective input management plays a critical role in enhancing crop output. These studies underscore the importance of fertilizers and pesticides in improving agricultural production and economic viability. Enhancing access to these inputs could further elevate crop output value, contributing to food security and sustainable agricultural development in Rwanda. That is consistent with broader research, such as Croppenstedt et al. (2013), which highlighted the importance of access to inputs, particularly fertilizers, in boosting crop production, especially for female-headed households.

However, it is important to acknowledge that excessive use of fertilizers and pesticides can lead to nutrient imbalances and environmental concerns, as noted by Zhang et al. (2015) and Chen,

[4] Descriptive statistics for the study variables are presented in Table 4 in the appendix.

Huffman, and Rozelle (2009). Therefore, while these inputs are beneficial, optimizing their use and monitoring potential environmental impacts is essential. An integrated land management strategy, incorporating organic matter enhancement, improved moisture retention, and careful use of inorganic fertilizers, is crucial for sustainable production gains. Furthermore, targeted extension services can help farmers refine their input management strategies, ensuring both increased output and long-term environmental sustainability, as suggested by Sakho-Jimbira and Hathie (2020).

The results reveal a significant positive linear relationship between land size and crop output value. However, the negative squared term indicates diminishing returns beyond an optimal threshold, revealing that land size expansion initially raises relative crop output value, but their impact becomes less pronounced with increased hectares of land, suggesting that expanding land size helps up to a point, but after that, it does not appear to enhance productivity and may even cause a slight reduction in crop output value. Understanding these dynamics is crucial for improving farm policy. The result highlights the need for strategic land management. This finding aligns with studies by Ali and Deininger (2015), Gollin (2019) and Giller et al. (2021) who observed that while increased land size improves productivity, larger land holdings can result in diminishing resources and labor returns. Furthermore, Byiringiro and Reardon (1996) and Jayne, Chamberlin, and Headey (2014) observed that Rwandan farmers, and those in Sub-Saharan Africa more generally, often face diminishing returns on larger landholdings due to complexities in managing resources and labor effectively.

These findings underscore the need for targeted agricultural policy to optimize land use while ensuring environmental sustainability. Promoting agroecological practices such as intercropping, agroforestry, and conservation agriculture can enhance productivity, maintain soil health, and protect the environment. For instance, initiatives that encourage crop diversification are essential for maximizing land utility and mitigating risks associated with monocropping, thereby strengthening resilience to market and climatic shocks. Additionally, integrating GIS technology and advanced data analytics for land-use monitoring and policy assessment can facilitate adaptive, evidence-based interventions tailored to the evolving needs of farmers and local contexts.

Table 1: Key determinants of crop output value from maximum likelihood estimations

Inputs Variables	coefficient	Standard error
Seed cost	0.01	0.02
Fertilizer and pesticide cost	0.31***	0.07
Labor cost	-0.03	0.06
Farm size	0.64***	0.03
½ (Seed cost)^2	0.09**	0.04
½ (Fertilizer and pesticide cost)^2	-0.01	0.02
½ (Labor cost)^2	0.06***	0.01
½ (Farm size)^2	-0.18***	0.05
Seed cost * Fertilizer and pesticide cost	-0.01	0.02
Seed cost*labor cost	-0.02	0.02
Seed cost*farm size	-0.002	0.02
Fertilizer and pesticide cost*labor cost	-0.003	0.03
Fertilizer and pesticide cost*farm size	-0.06*	0.03
Labor cost*farm size	0.07**	0.03
Constant	5.4 ***	0.1
Observations	2,006	

Source: Authors' calculations.

The results also indicated that while the linear relationship between seed use and crop output value is not significant, the positive and significant squared term reveals a non-linear effect. This suggests that seed use only begins to substantially enhance crop output once a certain threshold is reached. In other words, underuse or overuse of seeds is inefficient—optimal seed application is essential for maximizing production efficiency. This finding underscores the importance of precision seed management in improving crop productivity. Achieving higher agricultural returns requires not only the correct amount of seed, but also a broader, integrated approach that includes factors such as soil quality, complementary inputs (fertilizers, pesticides), and efficient farming practices. This conclusion is consistent with Kumbhakar et al. (2015), who stressed that seed input alone cannot address low agricultural productivity. Rather, it must be optimized within a framework that considers the interplay of various inputs. Moreover, McGuire and Sperling (2016) highlighted that the benefits of high-quality seeds are significantly amplified when combined with effective management and appropriate input levels. Therefore, providing farmers with better access to extension services and input becomes crucial in helping them fine-tune their seed use and, in turn, increase crop output value. These findings reinforce the need for targeted agricultural interventions that focus on optimizing input use to achieve sustainable productivity gains.

The findings revealed that while labor alone does not significantly affect crop output value, its effectiveness increases beyond a certain threshold, highlighting the importance of optimal labor utilization. This suggests that improved management practices and the integration of labor with complementary inputs are essential for increasing the economic value of produced crops. Moreover, the positive correlation between labor use and farm size implies that labor productivity increases with larger land sizes, likely because labor is better utilized on larger plots, enabling economies of scale or better allocation of tasks. This finding aligns with Haggblade et al. (2010), who observed that in Sub-Saharan Africa, productivity on larger landholdings increases with expanded labor allocation. Additionally, Hazell (2017) underscores the importance of strategically integrating labor with other inputs to boost crop output value. For smallholder farmers in Rwanda, leveraging extension services to optimize labor use and farm management practices is crucial for unlocking crop production gains.

3.3 Technical efficiency in smallholder farmers: Insights from stochastic frontier analysis of crop output value in Rwanda

This section presents the results of a stochastic frontier analysis to assess smallholder farmers' ability to maximize the economic value derived from their crop production. Instead of focusing on physical crop output only, we evaluate the monetary value of output, considering both the quantity and the market value of the crops produced, with input use represented by household expenditure on inputs. This approach offers a nuanced perspective on how effectively smallholders can convert their resources—such as land, labor, and capital—into the highest possible monetary value of production. By focusing on output value efficiency, this analysis addresses land and income constraints while supporting greater commercialization and sustainable growth.

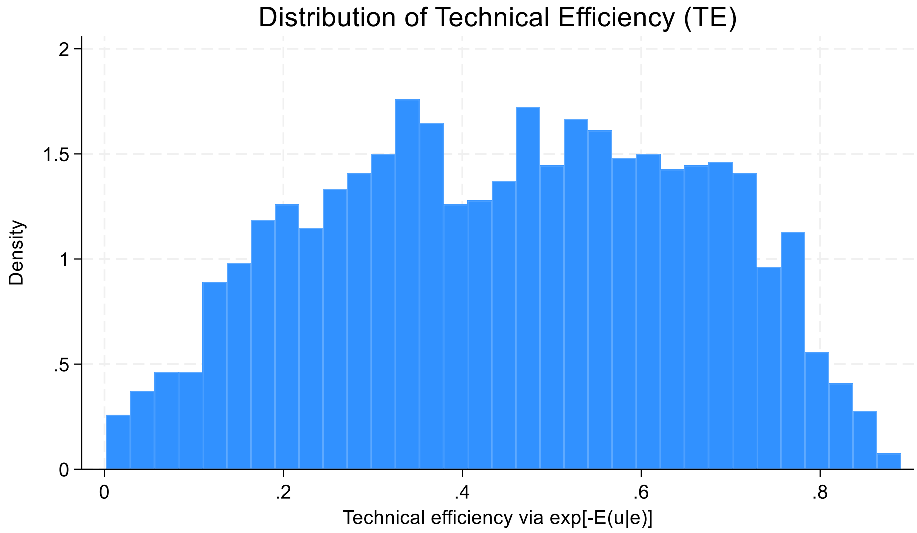
Table 2 presents the technical efficiency scores for smallholder farmers in Rwanda, assessing how effectively they utilize inputs such as land, seeds, labor, fertilizers, and pesticides to maximize crop output value. These scores reveal performance gaps and highlight critical areas for targeted interventions, informing strategies to enhance resource efficiency and promote sustainable growth in the smallholder farming sector.

Table 2: Technical efficiency of smallholder farmers in Rwanda: Maximizing crop output value

	Mean	Std	Min	Max	% farms with TE > 0.5	Observation
Technical Efficiency-TE						
All households	0.45	0.205	0.002	0.890	43.4	2,006

Source: Authors' calculations.

Figure 1: Distribution of Technical Efficiency



Source: Authors' calculations.

The analysis shows that smallholder farmers in Rwanda have an average technical efficiency (TE) score of 0.45, indicating farms are operating at just 45% of their potential and only 43% of households achieving a TE above 0.5, there is substantial room for improvement in resource use and output generation. This finding aligns with broader agricultural trends across Africa, where smallholder farmers consistently struggle to reach their full production potential due to various constraints such as limited access to inputs, financial resources, and modern farming techniques. For example, Adom and Adams (2020) found that the average TE among smallholder farmers across 49 African countries was only 38.2%, indicating that approximately 62% of their potential agricultural output remains unrealized. Similarly, Chirwa (2007) observed a TE of 46.2% among smallholder maize farmers in Malawi, largely attributed to limited access to modern inputs and technologies. The study underscores the need for targeted interventions, such as improved access to extension services, technology adoption, and policy support, to enhance crop production value and close the efficiency gap.

In Rwanda, lower efficiency scores may be partly due to the focus on subsistence or low-value crops rather than market-oriented or high-value crops (Mugabo and Warner, 2024; Warner et al., 2024). This focus on subsistence farming restricts farmers from optimizing input use and achieving higher crop output values, as Sell (2018) noted that smallholder farmers are often constrained by household labor demands. The study by Ngango and Hong (2021) further highlights that access to subsidies and improved inputs significantly boosts technical efficiency, suggesting that many Rwandan farmers need these crucial supports.

3.4 Factors influencing crop output technical efficiency

Understanding the determinants of technical efficiency is essential for enhancing the economic returns of crop production among smallholder farmers in Rwanda. Table 3 presents the Tobit model results, identifying critical factors that influence technical efficiency in terms of crop value. The analysis reveals that household size, access to extension services, participation in the Smart Nkunganire System, irrigation practices, land use consolidation, land ownership, and monocropping positively impact technical efficiency. Conversely, the gender of the household head, wage income, and distance to market exert a significant negative effect on technical efficiency. These findings are pivotal in shaping the ability of smallholder farmers to maximize crop value. By focusing on these determinants, policy makers and stakeholders can develop targeted strategies to optimize resource allocation, thereby increasing technical efficiency and enhancing economic returns in the agricultural sector.

The results in Table 3 reveal a positive and significant association between larger household sizes and higher technical efficiency (TE) in maximizing crop output value. This underscores the critical role of family labor in farm activities, particularly in mitigating financial constraints that may limit the hiring of additional labor and likely reflects family labor's role in enhancing farm management and optimizing input utilization, thereby boosting technical efficiency. This is supported by the findings of the stochastic frontier analysis which highlight the positive synergy of labor with land expansion in boosting crop output value. The finding is also consistent with Kamau (2007), who noted that in smallholder farming systems, where hiring external labor is challenging, family labor plays a vital role in offsetting financial limitations.

Similarly, Mechri and Cachia (2017) observed that larger households can generally allocate labor effectively, enhancing resource use. However, the results contrast with Alene and Coulibaly (2009), who found that smallholder farmers with limited landholdings and large family sizes struggled with efficiency due to poor labor allocation and restricted access to inputs. These mixed findings emphasize the critical role of both effective labor management and sufficient input access in improving technical efficiency in smallholder farming systems. When family labor is well-managed and adequately supported by inputs and subsidies, it can significantly enhance efficiency in maximizing crop output value among smallholder farms.

The analysis also demonstrates that access to extension services significantly enhances technical efficiency among smallholder farmers in Rwanda, directly influencing farmer’s optimization of crop output value. This can be explained by the fact that agricultural extension services encompass training and practical guidance in areas such as agronomy, crop protection, efficient input use, soil management, and various other activities to enhance farming practices. This aligns with Ahmadzai (2017), who noted that effective extension services improve farming outcomes through knowledge transfer and resource optimization. Similar findings by Amaza and Iheanacho (2006) and Bravo-Ureta and Pinheiro (1993) further support the positive relationship between extension services and technical efficiency in food crop production and is supported by additional research (Alwarritzi et al. 2015, Solís et al. 2009, Tipi et al. 2009, Seyoum et al. 1998).

To maximize these benefits, it is essential for governments and stakeholders to invest in agricultural extension programs. This includes enhancing the training of extension agents to provide tailored, user-friendly guidance for less literate farmers (Sakho-Jimbira and Hathie 2020). Additionally, promoting the Customized Agricultural Extension System (CAES) can play a key role in ensuring that farmers across different value chains receive tailored advisory services. This initiative encourages collaboration among the government, private sector, and research institutions to facilitate knowledge transfer and innovation. Given the proven link between extension services and improved efficiency, sustained investment in these programs is crucial to maximizing their impact and boosting agricultural productivity.

Table 3: Projected socio-economic effects on technical efficiency

Effect	Socio-economic variables
Positive effect	Household size
	Extension services access
	Smart Nkunganire System (SNS)
	Irrigation application
	Monocropping pattern
	Participation in Land Use Consolidation (LUC)
	Household own land
Negative effect	Access to wage income
	Distance from home to market
	Household head gender

Source: Authors' calculations.
Note: Smart Nkunganire Services: Rwandan digitalized agriculture input supply chain; A detailed table is available in Appendix Table 5.

The analysis indicates that participation in the Smart Nkunganire System significantly enhances technical efficiency among farmers, particularly regarding crop output value. This improvement reflects the SNS's effectiveness in digitalizing the agricultural input supply chain and increasing access to subsidies, financial services, and insurance. These findings align with the objectives of the Ministry of Agriculture and Animal Resources, emphasizing the SNS's role in enhancing efficiency and transparency within the agro-input subsidy program, ultimately boosting agricultural returns. Supporting literature further substantiates these results. Chirwa and Dorward (2013) highlight the essential role of subsidies in increasing technical efficiency among smallholders, while Choruma et al. (2024) and Abiri et al. (2023) demonstrate that input supply platforms like the SNS empower farmers to make informed decisions and allocate resources effectively. This aligns with broader African contexts where digital agricultural platforms enhance input distribution and farm management (Islam, Muzi, & Rodriguez Meza, 2018; Bångens & Söderberg, 2011).

However, while the expansion of digital technologies has progressed significantly, challenges such as high connectivity costs, limited infrastructure, and digital illiteracy in rural areas continue to hinder widespread access. Kropff et al. (2021) underscores the importance of addressing these barriers to fully leverage digital solutions and ensure that all farmers can benefit from these advancements. Overall, this study underscores the critical role of digital innovations, such as the SNS, in improving agricultural efficiency and crop production returns in Rwanda. To capitalize on these successes, the Government of Rwanda should expand the SNS's reach and increase subsidies, thereby further enhancing efficiency and supporting sustainable agricultural development.

The results indicate that irrigation significantly enhances technical efficiency, highlighting its crucial role in optimizing crop output value. This finding aligns with the Ministry of Agriculture and Animal Resources (MINAGRI) 2023 report, which emphasizes the importance of irrigation considering Rwanda's vulnerability to climate variability. Expanding irrigation infrastructure is essential for enhancing agricultural efficiency in the country. Furthermore, Warner et al. (2024) found that smallholder farmers who utilize irrigation are more likely to engage in high-value crop production and achieve greater levels of commercialization. Supporting this, Morais et al. (2021) and Kalli (2024) demonstrate that farms implementing irrigation practices consistently attain higher technical efficiency. Given these insights, it is imperative for policymakers to prioritize the adoption of irrigation technologies. Implementing supportive policies will not only enhance crop production efficiency but also ensure that smallholder farmers can maximize the economic value of their output in Rwanda.

Monocropping demonstrates a positive and significant effect on technical efficiency in this study. This approach, which involves concentrating on a single crop on a plot of land, facilitates more effective resource management and ultimately contributes to higher crop output value. This result suggests that households practicing monocropping can allocate resources more strategically, streamline input use, and concentrate their expertise on one crop, leading to greater efficiency in crop production. By reducing the operational complexity of managing multiple crops, it enhances labor allocation and simplifies farm management. This finding aligns with previous research showing that monocropping can lead to more specialized agricultural practices and better input optimization. For instance, Ngango and Kim (2019) found that the adoption of monocropping systems allowed for precise application of inputs, reducing inefficiencies in crop production. Their study on coffee farmers in Rwanda similarly demonstrated that improved cropping systems contribute to higher technical efficiencies. Moreover, Muimba-Kankolongo (2018) highlighted the advantages of monocropping for tasks like weeding, harvesting, and pest control, which are made easier when resources are concentrated on a single crop. However, it is crucial to recognize that while monocropping offers operational advantages, it also introduces risks such as increased vulnerability to pests, soil degradation, economic instability, and climate-related uncertainties. Thus, balancing monocropping's positive effects on technical efficiency with strategies to mitigate these risks is essential for long-term sustainability.

The positive and significant effect of land use consolidation on technical efficiency highlights the benefits of reducing land fragmentation and increasing operational scale. Consolidated plots allow for more efficient integration of inputs and services, leading to higher crop output value.
This finding aligns with Hakorimana and Akcaoz (2018), who demonstrated that land consolidation enhances efficiency by optimizing resource use and streamlining farm operations in Rwanda. Moreover, studies by Asiama et al. (2021) and Nilsson (2019) confirm that consolidated land improves crop management and operational efficiencies in Sub-Saharan Africa. These insights reinforce the critical role of land consolidation as a strategy to boost technical efficiency among smallholder farmers in Rwanda, by enabling better resource allocation and higher returns on inputs.

The analysis also reveals that secure land ownership, particularly through formal titles, significantly enhances technical efficiency in maximizing crop output value among smallholder farmers in Rwanda. This finding aligns with Atwood (1990), who demonstrated that secure land tenure encourages investment in land improvements and fosters effective management practices. Similarly, Mdoda and Gidi (2023) reported that full land ownership is associated with higher returns compared to rented land, suggesting that ownership incentivizes farmers to maximize the economic potential of their land. Byamugisha (2016) further supports this notion, indicating that formalizing land rights enables previously low-productive farmers to utilize their land more effectively, whether through improvements or rental arrangements. These findings underscore the critical role of land title security in enhancing technical efficiency in Rwanda's agricultural sector. While Rwanda's land title policy has successfully increased efficiency in maximizing returns from crop output among smallholder farmers, further efforts are essential to reinforce policies that promote formal land ownership like formalizing land leasing and establishment of community land banks where unused land can be temporally allocated for farming.

The negative relationship between wage income and technical efficiency in crop output value, suggests that households with wage income may divert resources away from farming, reducing their agricultural efficiency. This shift in focus from farming to wage labor likely leads to less attention to crop management and suboptimal use of inputs such as seeds, labor, and fertilizers. Consequently, households relying on wage income may not fully capitalize on agricultural support programs like subsidies and extension services, undermining their potential for maximizing crop output. These findings align with studies by Abdulai and Eberlin (2001) and Abdulai and Huffman (2000), which show that non-farm employment can reduce production efficiency by shifting priorities away from agriculture. The implications of these findings are critical, particularly in regions where agricultural subsidies and support programs are central to smallholder farming strategies. Our results emphasize the need for policies that balance the encouragement of diverse income streams with efforts to maintain agricultural efficiency. Households must be incentivized to optimize crop output despite having alternative income sources, ensuring the benefits of government support programs are fully realized, ultimately enhancing technical efficiency in crop production.

In addition, the results reveal that greater distance to markets significantly reduces the technical efficiency of smallholder farmers. This finding highlights the considerable barriers these farmers face in accessing both input and output markets. Long distances lead to higher transportation costs, logistical delays, and increased transaction costs, which hinder efficient farming operations. Farmers located farther from markets experience delays in purchasing necessary inputs, which disrupt optimal planting schedules and diminish potential yields. For households primarily focused on crop production, the adverse effects of market distance are even more pronounced. The extended time and costs associated with transporting crops to market reduce their ability to quickly respond to market demand, affecting income generation and overall efficiency.

Increased inefficiency created by market distance is not only a function of increased operational costs but also of reduced motivation to engage in profit-maximizing activities, as Abdulai and Huffman (2000) observed. Their work aligns with our findings, demonstrating that farmers with limited access to markets tend to underperform in terms of efficiency. Furthermore, the negative impact of market distance on efficiency is consistent with other studies, such as those by Sibiko et al. (2013) and Binam et al. (2004), which highlight the importance of market proximity in boosting efficiency through timely input use and better market responsiveness. These findings point to the need for policies that improve rural infrastructure and market access for smallholder farmers in Rwanda. By addressing these logistical challenges, policymakers can enhance the technical efficiency of farmers, ensuring more timely input usage, higher crop output value, and ultimately, better livelihoods for smallholder households.

Additionally, the results indicate a negative and significant effect of female household heads on technical efficiency, highlighting persistent gender disparities in agricultural efficiency. Female-headed households face significant socio-economic challenges that hinder their agricultural productivity. They often bear a heavy workload while having limited access to essential resources such as inputs, credit, and extension services, all of which are critical for effective farm management. These constraints, compounded by additional household responsibilities, can limit their ability to optimize farm management and reduce their technical efficiency. The finding aligns with Quisumbing and Maluccio (2003), who emphasized that gender disparities in access to productive resources contribute to lower technical efficiency among female-headed households in developing regions. These results underscore the critical need for targeted interventions and tailored agricultural support to address gender-related barriers, improve resource access, and enhance productivity and resilience.

The findings from the stochastic frontier analysis suggest that fertilizers, pesticides, and seeds are key drivers of crop output value, while labor also plays a significant role, especially on large farms. However, the diminishing returns to land expansion highlight the need for more efficient land management strategies. Policymakers should focus on optimizing resource use and labor allocation to sustain and enhance crop output value while managing land expansion more effectively. However, the results suggest substantial inefficiencies in current farming practices. The average technical efficiency across farmers is only 0.45, indicating that farms are achieving less than half of their maximum possible crop output value given the same input levels. In fact, only 43% of households achieved a TE greater than 0.5, highlighting significant room for improvement.

Moreover, the Tobit model highlights key strategies to enhance smallholder farmers' technical efficiency. Strengthening family labor capacity, improving access to extension services, and expanding initiatives like the Smart Nkunganire System are vital. Promoting irrigation, land consolidation, secure land ownership, and monocropping can further maximize crop output value. Addressing barriers such as efficiency gaps among female-headed households, labor diversions due to wage income, and limited market access is equally critical. These findings call for inclusive, targeted policies that empower farmers, address structural inefficiencies, and sustainably boost agricultural returns.

4. CONCLUSION

Rwanda's agricultural sector has implemented various interventions aimed at enhancing crop output value; however, there has been limited examination of how these efforts impact the overall technical efficiency of smallholder farmers. This study seeks to fill this gap by employing stochastic frontier analysis to evaluate the technical efficiency of smallholder farmers in Rwanda, with the aim of maximizing crop output value through the optimal use of available inputs. This study goes beyond simply increasing crop output and explores strategies to enhance the value of crop output produced. The goal is to better inform the Rwandan government how to increase farm output value among smallholder farmers. This could ease the issue of small landholdings production efficiency as more valuable crops will lead to high output value, increasing the returns from crop production and improving smallholder income, a fundamental driver of agricultural transformation and the basis of PSTA 5’s theory of change.

The analysis identifies critical inputs influencing crop output, including land size, seeds, labor, and fertilizers and pesticides use. Additionally, the findings indicate that the contributions of labor and seeds become increasingly significant with higher utilization levels. Conversely, the results suggest that exceeding a certain threshold in land expansion may lead to reduced crop output value, highlighting the importance of optimizing land use to avoid diminishing returns. The study also reveals that Rwandan smallholder farmers operate at an average TE score of 0.45, highlighting significant inefficiencies in achieving optimal production, with only 43% of households attaining a TE above 0.5. A Tobit model analysis evaluates the influence of various socioeconomic factors on TE, identifying critical determinants such as household size, access to extension services, participation in the Smart Nkunganire System, irrigation practices, land consolidation, and land ownership. Conversely, negative impacts on TE are associated with the gender of the household head, wage income, and distance to markets.

These findings underscore the importance of targeted interventions to enhance technical efficiency among smallholder farmers in Rwanda. Policymakers should strengthen access to agricultural extension services to educate farmers about efficient practices and optimize resource allocation, which can positively impact TE. Promoting participation in support programs like the Smart Nkunganire System can empower farmers with resources and information that enhance productivity and efficiency. Additionally, addressing gender disparities in access to resources and decision-making is vital, with policies aimed at empowering female-headed households, which often face additional barriers to achieving technical efficiency. Improving market access through infrastructure investment will help mitigate the negative effects of distance on efficiency, enabling improved access to inputs and for farmers to sell their products at fair prices.

Finally, encouraging sustainable land management practices and land consolidation can help maximize efficiency, particularly given the non-linear relationships observed with land size. By adopting these strategies, stakeholders can create an enabling environment that enhances technical efficiency, ultimately improving agricultural productivity and economic returns for smallholder farmers. Understanding the influence of socioeconomic factors on TE is essential for developing effective policies that support the growth and sustainability of the agricultural sector in Rwanda. This study provides a foundational analysis using data from the 2022 Smallholder Commercialization Survey, contributing valuable insights to inform future agricultural policy and interventions.

5. RECOMMENDATIONS AND IMPLICATIONS

1. **Optimize household labor utilization**
    - **Enhance labor productivity:** Implement training programs focused on efficient farming practices and task management to maximize the productivity of larger household sizes. Introduce incentives or subsidies for hiring additional labor during peak seasons.
    - **Family-focused policies:** Design agricultural policies that support family-based farming practices by providing targeted subsidies for labor-saving technologies tailored to assist households facing labor shortages such as older female-headed households.
    - **Community labor support:** Develop cooperative labor-sharing initiatives and community labor days to pool resources and reduce individual burdens. Introduce simple labor-saving technologies for older farmers.

2. **Optimizing labor use for higher productivity**
    - **Promote appropriate mechanization and labor-saving technologies** to improve labor productivity and reduce reliance on inefficient manual farming practices.
    - **Encourage youth engagement in agriculture** through incentives, skills training, and entrepreneurship programs to create a more efficient agricultural workforce.

3. **Strengthening agricultural extension services**
    - **Enhance the Implementation of the Customized Agricultural Extension System (CAES):** Strengthen coordination among the government, private sector, and research institutions to improve farmer access to tailored, demand-driven advisory services across value chains, with a focus on specialized support for different household types, such as youth-led farms, by promoting market-oriented practices and efficient resource use.
    - **Promote high-value crop production:** Encourage the cultivation of high-value crops per hectare by providing farmers with the knowledge and resources to reduce risks associated with market fluctuations and climate variability. This could include

offering insurance options, improved seeds, and access to markets, ensuring that farmers can produce more profitable and resilient crops.

- **Promote Public-Private Partnerships (PPPs):** Encourage investment from private sector players to scale up innovative extension approaches and increase farmer outreach.
- **Enhance Digital, Entrepreneurial, and Training Approaches:** Integrate ICT-based solutions and market-driven extension models to improve accessibility and efficiency. Launch innovative training programs on advanced crop management and sustainable techniques, partnering with farmer networks to expand outreach and adoption.

4. **Enhancing access to improved inputs and knowledge**
   - **Broaden input subsidies:** Scale up the Smart Nkunganire System to ensure equitable access to essential inputs, particularly for less commercialized households.
   - **Timely delivery and access:** Improve the digital infrastructure for better data collection and input delivery. Consider subsidies for modern agricultural technologies to boost productivity.
   - **Strengthening farmer cooperatives** to enhance collective input procurement, reduce costs, improve accessibility, and increase bargaining power for better market opportunities.

5. **Facilitate access to irrigation**
   - **Invest in infrastructure:** Expand irrigation facilities by developing small-scale systems and providing water management training. Offer subsidies for installation and maintenance.

6. **Improving efficiency in mixed farming systems**
   - **Promote farm specialization programs that help farmers optimize either crop or livestock production rather than splitting resources inefficiently**. Develop training programs that focus on optimizing resource allocation and crop specialization.
   - **Develop integrated farming models** that provide technical guidance on balancing crop-livestock interactions to enhance productivity.
   - **Expand livestock extension services** to ensure that households engaged in commercial livestock farming receive adequate support.

7. **Strengthen land use and security for smallholder farmers**
   - **Promote group landownership models:** Encourage cooperatives or associations to formalize group landownership and usage rights for small-scale farmers, particularly for communal resources like irrigation systems.
   - **Land leasing program:** Establish a matchmaking service to connect underutilized landowners with those seeking additional land, facilitating mutually beneficial agreements.
   - **Establishing community land banks:** To enhance land ownership security by pooling underutilized or disputed land for redistribution or productive use, providing farmers with equitable access to land resources, and fostering sustainable agricultural development.
   - **Link land security to access to finance:** enabling farmers to secure credit for agricultural investments, while also developing government-backed guarantee schemes to mitigate risks for lenders.

- **Encourage agroecological practices** such as crop rotation, intercropping, and conservation agriculture to improve land productivity.
- **Technical support for land management:** Strengthen land use planning by leveraging digital mapping and geospatial technology to optimize land allocation and sustainability.
- **Establish regional training hubs** to provide workshops on large-scale farming, sustainable land management, and cooperative governance while offering financial and technical incentives to encourage best practices in land consolidation and resource optimization.

8. **Enhance seed strategies**
   - **Educate improved seed utilization:** Inform farmers about optimal seed usage thresholds and provide access to high-quality seeds through subsidies.

9. **Promote gender-inclusive policies**
   - **Targeted interventions for women:** Implement gender-sensitive extension services and facilitate access to microcredit for female farmers. Support the formation of women-led cooperatives and provide childcare services to alleviate burdens on female farmers.

11. **Integrate wage income with farming**
    - **Flexible farming support:** Develop programs that allow for flexible work arrangements to balance wage employment with agricultural activities and offer financial literacy programs to reinvest wage income into farming.

12. **Strengthening market access and climate resilience**
    - **Improve market linkages** by investing in rural infrastructure, roads, and storage facilities to reduce post-harvest losses and market access costs. Establish digital platforms to link farmers directly with markets.
    - **Enhance climate-smart agriculture initiatives** to help farmers mitigate risks associated with climate variability, ensuring sustainable and stable production.
    - **Strengthen financial services** such as microfinance, insurance, and credit programs to enable farmers to invest in productivity-enhancing inputs and technology.

13. **Implement monitoring and evaluation systems**
    - **Improve data-driven adjustments by establishing** regular monitoring systems to assess the effectiveness of interventions. Utilize data to refine policies and address inefficiencies in productivity and resource use.

14. **Farmer engagement in policy dialogue and implementation**
    - Facilitate and empower farmers, to actively participate in agricultural policy dialogues, provide informed feedback on implementation challenges, and collaborate with policymakers to develop and refine effective, inclusive, and sustainable farmer-centered policies.

These recommendations maintain a focus on practical interventions that can lead to increased crop output and improved technical efficiency, while addressing the unique challenges faced by smallholder farmers in Rwanda.

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7. APPENDIX

Table 4: Summary of input-output data used in the stochastic production frontier

Variable	**Mean**	**Min**	**Max**
Crop output value (USD)	190.6	0	3,069.5
Seed cost (USD)	10.0	0	133.9
Fertilizer and Pesticide cost (USD)	33.0	0	264.6
Labor cost (USD)	33.3	0	1,774.8
Farm size (ha)	0.3	0.015	6.6
Observations	2,006		

Table 5: Summary of principal variables of technical efficiency used in the Tobit model

Household characteristics	
Household size (mean)	4.4
Household head age (years)	49
Femal7e household head (%)	30.2
Household head literacy (%)	66.6
Access to wage income (%)	62
Program participation	
Extension service access (%)	73
Twigire Muhinzi (%)	6
Smart Nkunganire Services (%)	29
Farmer field school (%)	8
Cooperative member (%)	14
Participation in Land Use Consolidation (%)	17
Farm characteristics	
Livestock production (%)	74.7
Irrigation application (%)	9.4
Monocropping pattern (%)	97
HH own land (%)	89.3
Distance home to market (minutes)	71.8
Altitude (100 m.)	1,734.8
Variation of rain (5-years average) (mm)	39.7
Observations	2,006

Note: HH: Household; * significant at 10%; ** 5%; *** 1%

Table 6: Determinants of technical efficiency in crop output across Rwanda's farm types: Tobit model insights

Socio-economic factors	Coefficient	Standard error
Household size	0.06*	0.03
Female household head	-0.1***	0.04
Household head age	-0.007	-0.05
Household head literacy	0.007	-0.03
Extension service access	0.08**	0.04
Twigire Muhinzi	0.05	-0.07
Smart Nkunganire Services	0.09**	0.04
Farmer field school	0.01	-0.06
Cooperative member	0.06	-0.05
Livestock production	0.02	-0.04
Access to wage income	-0.07**	0.03
Irrigation application	0.15***	0.05
Monocropping pattern	0.51***	0.08
Distance home to market	-0.04**	0.02
Participation in Land Use Consolidation	0.07*	0.04
HH own land	0.21***	0.05
Altitude (100 m.)	-0.06	-0.05
Var. of rain (5-yr avg.)	-0.1	-0.09
Constant	-0.79	-0.58
Observations	2017	

Source: Authors' calculations.

Note: * significant at 10%; ** 5%; *** 1% ; Twigire Muhinzi:Farmer-to-farmer extension approaches-farmer promoters and farmer field schools; Smart Nkunganire Services (SNS): Rwandan digitalized agriculture input supply chain.

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