Research Article

Does Farmer Education Help Smallholder Coffee Farmers be More Technically Efficient? Evidence From Stochastic Frontier Analysis

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Abstract | This study addresses the global surge in coffee consumption, highlighting Indonesia's production fluctuations. Focused on smallholder farmers in East Java to assess the technical proficiency of small-scale Arabica coffee growers in the East Java Province's Bondowoso Regency. Utilizing the Maximum Likelihood Estimate (MLE) estimation method with the Frontier 4.1 program, data collected from 173 smallholder Arabica coffee farmers in the Bondowoso Regency, East Java Province, were analyzed using the stochastic frontier production function approach. Because 32.37% of Bondowoso's Arabica coffee farmers are technically inefficient, they have not been able to properly manage inputs. With the combination of inputs utilized, the remaining farmers have achieved technical efficiency and potential production. According to the farmers' educational attainment, this study separates the efficiency levels, and it is found that technically inefficient farmers can be found in both the low and high educational groups. Compared to previous studies, this one introduced the pruning variable, which has a substantial impact and seems to be a source of negative correlation with inefficiency. Technical inefficiencies occur less frequently the more coffee plants are pruned. Technical inefficiencies tend to decrease for older farmers, have more education, and have easy access to credit.

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Introduction

Coffee is the second most traded commodity in the world after crude oil, both in terms of volume and economic significance, making it one of the most valuable agricultural products in global history (Tamirat and Tadele, 2023). As one of the largest agro-industries worldwide, coffee brings together a wide range of stakeholders and geographic regions through an integrated global value chain (Setyobudi *et al*., 2021; Hidalgo *et al*., 2023). In Southeast Asia, particularly in developing countries, the agricultural sector plays a critical role as a primary source of employment and a key driver of economic growth (Andoko, 2020; Siahaan *et al*., 2022). The consistent rise in coffee prices over time further underscores the sector's importance in sustaining rural livelihoods and supporting national economies (Moeis *et al*., 2020).

At the national level, Indonesia's coffee sector holds a strategic position as one of the country's leading export commodities, engaging more than 1.8 million smallholder farming households. To address the persistent challenges of low productivity and competitiveness, the government through the Ministry of State Owned Enterprises (Kementerian BUMN) has launched the Coffee and Cocoa Nusantara Project Management Office (PMO), which aims to enhance the productivity and welfare of smallholder coffee farmers. The program is implemented in collaboration with *Perhutani* (the State Forestry Enterprise), which currently manages approximately 43,000 hectares of coffee cultivation areas within forest zones.

In parallel, the Directorate General of Estate Crops under the Ministry of Agriculture has implemented several national initiatives, including the National Movement for Coffee Production, Value Addition, and Competitiveness *(Gernas Kopi)*, the Smallholder Coffee Replanting Program, and the institutional strengthening of farmer groups through cooperatives *(Gapoktan)*. Despite these efforts, Indonesia's smallholder coffee productivity remains relatively low compared to other major producing countries. This situation highlights the necessity for more region-specific analytical approaches to assess the efficiency of input utilization and to identify the socio-economic and technical factors that drive production performance at the local level.

However, enhancing farmers' technical proficiency is equally critical for improving agricultural productivity. As noted by Battese and Coelli (1995); Khan *et al.* (2010); Poudel *et al.* (2015), and Ngango and Kim (2019), technology alone is insufficient without the technical capacity to utilize it effectively. According to Coelli *et al.* (2005), technical efficiency refers to a producer's ability to achieve maximum output from a given set of production inputs (Terefe, 2023). In this context, advancements in agricultural technology are particularly beneficial for developing countries such as Indonesia. Research by Mishra and Thakur (2022) highlights that challenges related to low output and productivity in the coffee sector can be effectively addressed by enhancing the technical efficiency of small-scale farmers. As smallholder farmers dominate the coffee farming landscape, improving their productivity and technical capabilities is crucial for the overall development of the sector (Binam *et al*., 2003; Qu *et al*., 2020). Moreover, economic analysis of farming systems plays a critical role in this process, as it helps reduce production costs while promoting both horizontal and vertical growth (Al-Aani, 2024).

A notable research gap persists in the limited number of empirical studies examining the level of technical efficiency and the factors influencing the productivity of smallholder Arabica coffee farmers at the regional level, particularly in Bondowoso Regency, East Java, Indonesia. Most existing research in Indonesia has concentrated on sustainability and certification aspects such as Fair Trade, Rainforest Alliance, or Geographical Indication while studies employing frontier approaches, such as the Stochastic Frontier Analysis (SFA), to measure technical efficiency remain scarce. Yet, technical efficiency constitutes a fundamental prerequisite for achieving sustainability. Without improving the efficiency of input utilization and resource management, sustainability certifications alone are unlikely to generate meaningful economic benefits for smallholder farmers.

One of the key sources of inefficiency in Bondowoso stems from the relatively low educational attainment and limited managerial capacity of Arabica coffee farmers, many of whom have completed only primary school. These conditions may hinder their ability to adopt agricultural innovations and to optimize resource use in production processes. To date, no empirical studies have specifically investigated the technical efficiency of Arabica coffee production in Bondowoso, nor have they examined its relationship with socio-economic factors such as education, farming experience, and access to agricultural information. Such insights are essential for evaluating farmers' performance and formulating effective, evidence-based policy interventions.

Accordingly, the main objective of this study is to identify and analyze the determinants of technical efficiency among smallholder Arabica coffee producers in Bondowoso Regency. The study seeks to make an empirical contribution to the growing body of literature on agricultural efficiency in Indonesia and to provide a scientific foundation for developing regionally tailored policies aimed at enhancing the productivity and competitiveness of smallholder coffee production systems.

Materials and Methods

This study employed cross-sectional data obtained from household surveys conducted in Bondowoso Regency, East Java Province, Indonesia. The research location is illustrated in Figure 1. The sample consists of 173 coffee farmers surveyed during the 2023 growing season. The research was conducted over a two-year period (2023–2024). A multiphase sampling technique was employed to ensure a representative and consistent sample of coffee growers. In the first stage, East Java Province was selected using purposive sampling due to its abundant natural resources and high concentration of coffee plantations. In the second stage, Bondowoso Regency was purposefully chosen because it has a relatively larger number of Arabica coffee farmers and plantations compared to other regencies in East Java. The third stage involved the purposive selection of the Sumberwringin district, known for its substantial number of coffee growers and extensive Arabica coffee cultivation. In the fourth stage, coffee farmers were selected for interviews using a simple random sampling method. Coffee is typically cultivated in tropical and subtropical climates, and in East Java, most coffee producers are small-scale farmers characterized by fragmented land ownership and multiple small plots.

Figure 1: *Main center of arabica coffee production in Bondowoso Regency, East Java Province*
Source: forestry and plantation department of Bondowoso Regency

Existing studies on the estimation of technical efficiency commonly utilize two primary approaches: non-parametric methods such as Data Envelopment Analysis (DEA), and parametric methods such as Stochastic Frontier Analysis (SFA). The results derived from these methods may differ slightly depending on the nature and structure of the data (Battese and Coelli, 1995; Coelli *et al*., 2005). However, Coelli *et al.* (2005) argue that SFA is particularly well-suited for assessing technical efficiency in agricultural research, especially in the context of developing countries. Compared to Ordinary Least Squares (OLS) regression, frontier models offer superior performance in analyzing efficiency (Abdullah *et al*., 2021). In this study, the Stochastic Frontier Analysis (SFA) approach, utilizing Maximum Likelihood Estimation (MLE), was applied to estimate a stochastic frontier cost function and to identify the key determinants of cost inefficiency (Al-Wasity *et al*., 2023; Al Hachami, 2022; Ali *et al*., 2022).

This approach allows for the simultaneous estimation of the production frontier and the inefficiency model using a one-stage method, thereby enabling hypothesis testing within a unified framework. In line with this, the present study employs the Stochastic Frontier Analysis (SFA) model to evaluate the level of technical efficiency and to identify the factors influencing it in Arabica coffee farming in East Java Province.

The stochastic frontier production function was initially developed by Meeusen and van den Broeck (1977) and later refined by Aigner *et al*. (2023). As defined by Coelli *et al*. (2005), the technical efficiency (TE) of each agricultural producer is measured as the ratio of the frontier output (Y*) to the actual observed output (Y). The model is expressed as follows:

$$TE_i = \frac{Y_i}{Y_i^*} = \frac{f(x_i;\beta)\cdot exp(v_i - u_i)}{f(x_i;\beta)\cdot exp(v_i)} = exp(-u_i),$$

$$Technical\ inefficiency_i = 1 - TE_i,$$

Technical efficiency (TE) ranges between 0 and 1, as the observed output is typically less than or equal to the frontier output. Coffee growers who achieve TE scores approaching 1 are producing at or near the maximum output level that is economically and technically feasible. According to Jondrow *et al.* (1982), the conditional expectation of the inefficiency term u_i also known as the disturbance component εi can be used to estimate the level of technical efficiency. This is presented in Equation (2) and has been widely applied in agricultural efficiency studies (Theriault and Serra, 2014; Mar *et al*., 2018).

$$E(u_i|\varepsilon_i) = \frac{\sigma_u\sigma_v}{\sigma}\left[\frac{f(\varepsilon_i\lambda/\sigma)}{1-F(\varepsilon_i\lambda/\sigma)} - \frac{\varepsilon_i\lambda}{\sigma}\right],$$

where $\sigma^2 = \sigma_u^2 + \sigma_v^2, \lambda = \sigma_u / \sigma_v$ and f(.) dan F(.) stand for the normal distribution's probability density function and cumulative distribution function, respectively. Parameter σ_u^2 and σ_v^2. estimates for the variance are obtained by applying Maximum Likelihood Estimation (MLE) to the production function given in equation (1).

This method was expanded upon by Battese and Coelli (1995), who proposed a model in which a few independent variables account for the variation in technical inefficiency (u_i). To obtain technical insufficiency (u_i), these authors proposed that it follows a truncated normal distribution with a mean of μ and a variance of truncated (at 0).

$$u_i = Z_i\delta + \omega_i,$$

where Zi represents the independent vector, and Ω indicates the vector of unknown coefficients to be estimated. Ωi is the random error term determined by a normal distribution with a mean of zero and an unknown variance, σ^2 (Yin and Wang, 2017)

SFA also allows for estimating the model for the impact of technical inefficiency. Based on the current state of coffee farming in Bondowoso Regency, East Java, and relevant literature, there are eight variables (i.e., Zi) considered in the technical inefficiency model, namely pruning, pest control, access to credit, farmer's age, education, the number of family dependents, and coffee farming experience.

Results and Discussion

Description of arabica coffee farmers

The findings of this study indicate that the majority of respondent farmers fall within a highly productive age group. As shown in Table 1, approximately 98.84% of the farmers are between 15 and 64 years old and possess considerable experience in cultivating Arabica coffee, with 62.43% having between five and ten years of farming experience. However, most of these farmers have only completed primary education, and their households typically have fewer than four dependents, reflecting a generally low level of formal education.

The technical effectiveness of growing arabica coffee

A production process that utilizes fewer inputs to generate the same level of output is a reflection of technical efficiency. In this study, the technical efficiency of Arabica coffee farming by smallholder farmers was analyzed using the Stochastic Frontier Production Function approach with the Maximum Likelihood Estimation (MLE) method, implemented through the Frontier 4.1 software. This approach aims to determine the actual production achieved in comparison to the potential production capacity of the farmers.

According to Coelli *et al.* (2005), a company is considered technically efficient if its technical efficiency index exceeds 0.70. Table 2 presents the results of the technical efficiency estimation for Arabica coffee farming by smallholder farmers in Bondowoso Regency. The lowest recorded efficiency value is 0.059, while the highest is 0.983. This indicates that a farmer with the lowest efficiency score would need to improve by 92.4% to reach the highest level of technical efficiency.

Table 1: *Characteristics of research respondents*

Characteristic	Number	Percentage (%)
Age		
<15 years old	0	0
15-64 years old	171	98.84
>65 years old	2	1.16
Farming Experience	39	22.54
<5 years	108	62.43
5-10 years	26	15.03
>10 years		
Formal Education	69	39.88
Elementary School	37	21.39
Junior High School	58	33.53
Senior High School	9	5.2
Undergraduate's Degree		
Number of dependents in the	97	56.07
family	76	43.93
<4 people	0	0
4-6 people		
<6 people		

Table 2 also shows that 56 respondents, representing 32.37% of the sample, are classified as technically inefficient, as their efficiency scores fall below 0.71. This inefficiency is largely attributed to suboptimal input management. On the other hand, 117 respondents (67.63%) are considered technically efficient. Specifically, 45 farmers fall within the efficiency range of 0.91–1.00, 53 within 0.81–0.90, and 19 within 0.71–0.80.

Table 2: *Distribution of technical efficiency in smallholder arabica coffee farming*

No.	Technical efficiency scores	Number	Percentage (%)
1.	≤ 0,60	50	28.90
2.	0,61 ≤ ET ≤ 0,70	6	3.47
3.	0,71 ≤ ET ≤ 0,80	19	10.98
4.	0,81 ≤ ET ≤ 0,90	53	30.64
5.	0,91 ≤ ET ≤ 1,00	45	26.01
Total		173	100
Average		0.716	
Minimum		0.059	
Maximum		0.983	

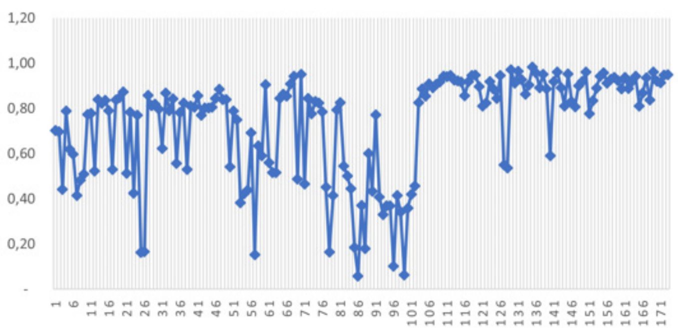

Figure 2: *Technical efficiency of arabica coffee farmers*

These results suggest that 117 farmers have achieved a technical efficiency score above the 0.70 threshold, indicating that they are producing close to the maximum output possible given their input combinations. On average, the technical efficiency of smallholder Arabica coffee farming in Bondowoso is 0.716, meaning that 71.60% of potential output is realized using current inputs and available technology. This implies that there is still room to increase output by 28.40%. Figure 2 provides a graphical illustration of the technical efficiency distribution among Arabica coffee farmers in the region.

The average technical efficiency index for Arabica coffee farming in Cameroon is estimated at 0.896, with 32% of surveyed farmers recording an index below 0.91 (Gama *et al*., 2015). In comparison, the technical efficiency index in the current research area is lower than this average. Small- and medium-scale coffee farmers are generally considered technically inefficient (Calvo, 2022). This overall low level of technical efficiency is largely attributed to the use of outdated agronomic practices and the limited availability of effective agricultural extension services (Zewdie *et al*., 2021).

This study categorizes technical efficiency values based on the educational attainment of coffee farmers. The education levels considered include six years of elementary school, six years of junior high school, nine years of senior high school, and seventeen years corresponding to a bachelor's degree. Education is recognized as a strong indicator of a farmer's ability to absorb new information, adopt innovations, and effectively apply new technologies to improve farming practices. Interestingly, high school graduates were found to be the most technically efficient group, surpassing even those with a bachelor's degree. Specifically, 49 farmers with a high school education achieved technical efficiency scores above 0.70, compared to only 8 farmers holding a bachelor's degree. A similar trend is observed among farmers with lower educational backgrounds. Among junior high school graduates, 23 individuals attained technical efficiency, while 37 elementary school graduates also managed to efficiently utilize inputs. However, the highest number of inefficient farmers defined as those with technical efficiency values below 0.70 were from the elementary school group, totaling 32 individuals. Notably, even among those with a bachelor's degree, 1 farmer (0.58%) was found to be technically inefficient in the use of inputs for Arabica coffee production.

The findings indicate that while a majority of Arabica coffee farmers in Bondowoso operate efficiently, there remains significant potential to improve productivity through better input management and knowledge transfer. The relatively moderate average technical efficiency score (0.716) suggests that most farmers are operating below the production frontier, primarily due to limited access to resources, technology, and technical guidance.

Education emerges as a critical determinant of efficiency. The higher technical efficiency among high school graduates compared to other groups implies that practical education and vocational-level understanding of agriculture may be more effective in improving farm performance than formal higher education alone. This supports the argument by Ureta *et al*. (2007) that education enhances managerial capacity and accelerates the adoption of improved technologies. However, the presence of inefficient farmers even among the more educated group highlights that education alone is insufficient without supporting systems such as continuous training, cooperative-based learning, and access to information technology.

Table 3: *The distribution of technical efficiency based on farmers' education*

Efficiency Score	Number	Percentage (%)
Elementary School		
≤ 0,60	28	16.18
0,61 ≤ TE ≤ 0,70	4	2.31
0,71 ≤ TE ≤ 0,80	3	1.73
0,81 ≤ TE ≤ 0,90	16	9.25
0,91 ≤ TE ≤ 1,00	18	10.40
Junior High School		
≤ 0,60	13	7.51
0,61 ≤ TE ≤ 0,70	1	0.58
0,71 ≤ TE ≤ 0,80	5	2.89
0,81 ≤ TE ≤ 0,90	9	5.20
0,91 ≤ TE ≤ 1,00	9	5.20
Senior High School		
≤ 0,60	8	4.62
0,61 ≤ TE ≤ 0,70	1	0.58
0,71 ≤ TE ≤ 0,80	10	5.78
0,81 ≤ TE ≤ 0,90	22	12.72
0,91 ≤ TE ≤ 1,00	17	9.83
Undergraduate Level		
≤ 0,60	1	0.58
0,61 ≤ TE ≤ 0,70	0	0.00
0,71 ≤ TE ≤ 0,80	1	0.58
0,81 ≤ TE ≤ 0,90	6	3.47
0,91 ≤ TE ≤ 1,00	1	0.58
Total	173	100

The relatively low efficiency compared to international benchmarks, such as Cameroon's 0.896 (Gama *et al*., 2015), indicates that Indonesian smallholders especially in Bondowoso still face systemic constraints. These include limited access to quality inputs (fertilizers, improved seedlings), inconsistent pest control, and weak extension service networks. Furthermore, institutional factors, including limited access to credit and unstable market prices, may exacerbate inefficiency by discouraging optimal resource use.

To enhance efficiency, future policy interventions should focus on strengthening farmer cooperatives, expanding access to credit, and providing targeted technical assistance. Incorporating precision agriculture and digital monitoring tools could further help optimize input allocation and reduce inefficiency. Additionally, training programs tailored to different education levels can bridge the knowledge gap and enable farmers to adopt more effective cultivation practices.

Table 4: *Sources of technical inefficiency in arabica coffee farming in bondowoso regency, 2023*

Variable	Expected Sign	Coefficient	t-ratio
Constant	+/-	15.49	12.69
Pruning	-	-1.057	-10.17
Pest control	-	-0.867E-6	-1.464**
Access to credit	-	-5,065	-9.890
Age	-	-0.372E-5	-4.204
Education	-	-1.233	-2.654
Number of family dependents	-	-0.234E-5	-2.691
Experience	-	-0.500	-1.498**
Sigma-squared	0.634		
gamma	0.988		
Log-likehood ratio	3.671		
LR test of the one-sided error	370.99		

Source: processed primary data, 2023
Note:
**) Significantly influences at a 5% level (1.654)*
***) Significantly influences at a 10% level (1.286)*

The factor of technical inefficiency in arabica coffee farming

Table 4 presents the results of the Maximum Likelihood Estimation (MLE) analysis of the sources of inefficiency. The MLE output shows a sigma-squared (σ^2) value of 0.634, which is relatively close to zero. When the sigma-squared value approaches zero, it suggests that the inefficiency error term (u_i) follows a normal distribution, indicating that the specified production function adequately fits the empirical data.

In this context, the gamma (γ) value represents the proportion of total variance attributed to technical inefficiency (u_i) relative to the combined variance of random noise (v_i) and inefficiency. The estimated gamma value is 0.988, which is very close to 1. This indicates that 98.8% of the total error in the model is due to technical inefficiency, while only 1.2% is due to random errors. A gamma value approaching 1 implies that the gap between actual and potential production is predominantly caused by technical inefficiency rather than random shocks or external factors not captured by the model. This finding aligns with previous studies in developing countries, which also reported that smallholder coffee production tends to suffer from structural and managerial inefficiencies rather than stochastic variations (Zewdie *et al*., 2021).

The Likelihood Ratio (LR) test is conducted to determine whether technical inefficiency effects are present in the model, thereby indicating whether overall technical efficiency has been achieved. Based on the analysis, the LR test yields a value of 370.99. This computed value is then compared with the critical value from the chi-square (X^2) distribution table. At a 5% significance level and with 9 degrees of freedom (corresponding to the number of restrictions), the critical chi-square value is 16.274.

Since the LR test statistic significantly exceeds the chi-square critical value, the null hypothesis (H_0), which assumes the absence of technical inefficiency effects, is rejected. This result confirms the presence of technical inefficiency in the model. It also suggests that either the cultivation technology employed does not exhibit constant returns to scale or that technical inefficiency significantly contributes to the variance of the disturbance term in smallholder Arabica coffee farming in Bondowoso Regency.

In the analysis of technical inefficiency effects, the sign of the coefficient is a key consideration, as outlined by Coelli *et al*. (2005). A positive parameter coefficient indicates that the associated variable contributes to increased technical inefficiency among farmers. Conversely, a negative coefficient suggests that the variable helps reduce technical inefficiency, thereby improving farmers' performance.

At the 10% significance level, the variables related to farming experience and pest control demonstrate a negative relationship with technical inefficiency, indicating a significant and beneficial impact on the efficiency of smallholder Arabica coffee farming in Bondowoso Regency. Notably, emphasis is placed on environmentally friendly pest management practices to ensure that Arabica coffee production remains ecologically sustainable.

Sustainability efficiency, as described by Massaquoi *et al*. (2022) and Skevas and Palomares (2023), reflects a farmer's ability to increase output while reducing environmental harm specifically by limiting fertilizer-related nitrous oxide emissions. Therefore, the environmental implications of these agricultural practices must be assessed to ensure long-term sustainable production. Similar findings were reported by Ali et al. (2022), Younas *et al*. (2024), and Khajjak *et al*. (2024), who also observed a negative correlation between farming experience and technical inefficiency. In Indonesia, this resonates with the government's emphasis on integrated pest management as part of the Sustainable Coffee Platform of Indonesia (SCOPI) initiative, which promotes eco-friendly cultivation practices and knowledge sharing among farmers.

At the 5% significance level, the variables of pruning, credit availability, age, education, and number of dependents exhibit a negative correlation with technical inefficiency, indicating a significant and efficiency enhancing effect. Specifically, increased pruning practices are associated with reduced inefficiency in coffee cultivation. These findings align with research on coffee production in the Philippines, where technical efficiency is significantly influenced by access to credit (Sabroso and Tamayo, 2022).

To address the persistent issue of limited capital among farmers, it is recommended that lending institutions provide greater support by offering soft loan schemes. Enhancements in household size, educational attainment, and credit accessibility have been shown to improve technical efficiency among coffee farmers (Anh *et al*., 2019). Notably, agricultural credit alone can boost technical efficiency by as much as 3.8% (Abdallah, 2016). Supporting this, Hassan *et al*. (2023) highlight that smallholder agricultural development programs play a key role in promoting efficiency by providing interest-free loans to farmers. Field observations indicate that 39.88% of Arabica coffee farmers have only completed primary education (elementary school), while just 5.2% have attained a bachelor's degree. These figures suggest that the overall education level among Arabica coffee farmers is relatively low. In general, higher education is expected to enhance farmers' technical and managerial capabilities. However, empirical evidence on the relationship between education and agricultural productivity is mixed. Studies by Nguyen *et al*. (2021); Alabi *et al*. (2023); Donkor (2023) and Muteti *et al*. (2023) argue that higher education may reduce technical efficiency, as more educated individuals often seek better employment opportunities outside agriculture, potentially decreasing the household labor available for coffee production. In contrast, other research including that by Akpaeti and Frank (2021); Battese and Coelli (1995); and Ali *et al.* (2022) disputes this view. These studies demonstrate that education significantly enhances farmers' productivity and their ability to utilize available technologies effectively.

Supporting this latter perspective, evidence from the Jimma zone shows that education has a substantial positive effect on farmers' technical efficiency. This may be because educated farmers can better assess and implement productivity-enhancing practices, although it is also possible that they may diversify into non-agricultural sectors, leading to less involvement in routine plantation tasks. On the other hand, farmers with lower educational attainment may remain more focused on agricultural work and, through basic skills, effectively manage coffee operations.

Furthermore, farmers who are older, more educated, and have better access to credit generally exhibit lower levels of technical inefficiency. Education enhances knowledge and skills, thereby contributing to reduced inefficiency. To improve coffee productivity, especially at the smallholder level, the adoption of appropriate technologies must be actively promoted. Technological advancements are essential for enhancing efficiency and increasing yields in Arabica coffee production (Yang *et al.*, 2022).

In the context of Bondowoso, the relatively low education level (only 5.2% holding a bachelor's degree) underscores the importance of continuous training and extension programs to bridge the knowledge gap and improve input management efficiency. From a policy perspective, the findings suggest that technical inefficiency among smallholder coffee farmers can be reduced through targeted interventions aimed at improving access to financial services, market information, and appropriate technologies. The Government of Indonesia has launched several initiatives to address these structural gaps, including the *People's Business Credit (KUR)* program, which provides low-interest loans for smallholder farmers; the *National Coffee Replanting Program (PPKN)*, which focuses on rejuvenating aging coffee trees; and multi-stakeholder partnerships under the *Sustainable Coffee Platform of Indonesia (SCOPI)*, which work collaboratively with the Ministry of Agriculture and private sector actors to strengthen training, certification, and sustainable production systems. Despite these efforts, the persistence of technical inefficiency observed in this study indicates that such programs have not yet been fully effective or equitably implemented across all coffee producing regions, particularly in remote and upland areas. Strengthening institutional coordination, expanding extension services, and improving farmers' inclusion in cooperative structures are therefore essential to ensure that national initiatives translate into tangible productivity gains and sustainable livelihoods for Indonesian coffee producers.

Conclusions and Recommendations

This study investigates the factors influencing the technical efficiency of Arabica coffee growers in Bondowoso Regency, East Java, Indonesia. To achieve this objective, the stochastic frontier production function is estimated using the Maximum Likelihood Estimation (MLE) method. The variables examined include pruning practices, pest control, credit availability, farmers' age, education level, number of dependents, and farming experience. These factors are found to significantly influence the level of technical inefficiency, with each playing a role in reducing inefficiency in Arabica coffee production within the study area.

The results indicate that the average technical efficiency index is 0.716, with 32.37% of farmers recording an efficiency index below 0.983. These findings suggest that Arabica coffee production in the region is not yet operating at full technical efficiency. On average, farmers could potentially increase their output by 28.40% if they optimize the use of available resources and operate closer to the efficiency frontier. Enhancing resource utilization could not only boost productivity but also offset potential price declines, ultimately contributing to higher incomes for coffee farmers.

As with most empirical research, the findings of this study should be interpreted in a relative rather than absolute context. The model employed is subject to limitations, particularly its exclusion of other relevant variables such as market imperfections and production risks that may also affect technical efficiency. Future research should incorporate additional explanatory variables such as access to farmer groups or cooperatives, participation in extension programs, access to information and communication technologies (ICTs), farm size, and soil quality indicators. Including these factors could provide a more comprehensive understanding of both institutional and farm-level determinants of technical efficiency. Moreover, incorporating a robustness check using alternative functional forms or estimation techniques would further strengthen the reliability and generalizability of the results.

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Novelty Statement

The lack of formal education among coffee farmers in Bondowoso has never been empirically studied in relation to technical production efficiency. This study offers a new perspective by investigating the extent to which education plays a role in promoting the efficiency of smallholder coffee farming.

Author's Contribution

Puryantoro: The manuscript was written, the data was collected and coordination was carried.
Yuli Hariyati: The manuscript was written and manuscript format was coordinated and coordination was carried.
Joni Murti Mulyo Aji: The data was analyzed and coordination was carried.
Fitriyaningsih: The data was collected and coordination was carried.

Generative AI or AI assisted technology statement
Generative AI or AI-assisted technologies were utilized in a limited manner to support the drafting process, including language refinement and structural organization. No AI tools were used to generate research data, analyze findings, or draw conclusions. The author assumes full responsibility for the accuracy, integrity, and originality of the content presented in this work.

Conflict of interest
The authors have no conflict of interest.

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