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BEYOND FERTILIZERS AND LABOR: UNDERSTANDING SOCIOECONOMIC DRIVERS OF TECHNICAL EFFICIENCY AMONG SMALLHOLDER OIL PALM FARMERS

Tengku Dede Rachma Sari[1*], Diana Chalil[1], Lindawati[1]
[1]Universitas Sumatera Utara, Jalan Dr. T. Mansur No.9, Medan 20222, Indonesia

[*]Correspondence E-Mail: tengkudede016@gmail.com
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ABSTRACT

The productivity of independent smallholder oil palm farmers remains significantly lower than that of corporate plantations, despite operating under similar agroecological conditions. This study aims to analyze the socioeconomic factors influencing technical efficiency among independent smallholders, focusing on the roles of education, farming experience, access to extension services, and household income. Using a quantitative explanatory design, the research applies the Cobb-Douglas Stochastic Frontier Analysis (SFA) model based on primary survey data from 125 smallholders in Dolok Masihul District, North Sumatra. Data were analyzed using Frontier 4.1 and STATA through a one-step procedure to assess the effects of socioeconomic characteristics on inefficiency. Results show an average technical efficiency of 0.78, suggesting a 22% potential output increase through better resource utilization. Land size and fertilizer use significantly enhance productivity, while labor and seed type exhibit moderate effects. Farming experience, education, and extension access significantly reduce inefficiency, whereas age and household size have no notable influence. The study's novelty lies in integrating an econometric model with a sociological perspective, demonstrating that smallholder efficiency is shaped by social capacities rather than agronomic factors alone. It advances a socio-econometric framework for understanding smallholder productivity and recommends policy interventions emphasizing human capital, farmer education, and community-based extension systems to foster sustainable rural development.

***Keywords**: Community Extension, Farming Experience, Independent Smallholders, Socioeconomic Factors, Technical Efficiency*

INTRODUCTION

The productivity of smallholder oil palm plantations in Indonesia has long attracted the attention of researchers and policymakers due to the substantial productivity gap compared to large-scale state-owned and private estates (Petri et al., 2024; Woittiez et al., 2024). Despite relatively similar agroecological conditions, smallholders often produce fresh fruit bunches (FFB) with both volume and quality considerably below industrial standards (Fauzi et al., 2025). This phenomenon raises a fundamental question: why does smallholder productivity remain low despite numerous policy interventions, such as fertilizer subsidies, technical training, and the distribution of high-yield seeds, implemented over the years? This question is crucial not only because oil palm is one of Indonesia's major export commodities but also because smallholders manage more than 40% of the country's total planted area (Simanjuntak & Chalil, 2025). Understanding the roots of technical efficiency at the smallholder level therefore represents a key step toward ensuring the sustainability of Indonesia's rural economy.

Empirical evidence suggests that input-based intensification approaches have not been entirely effective. For instance, field data from Dolok Masihul District indicate that the average productivity of independent smallholders reaches only 14–16 tons of FFB per hectare per year, far below the potential yield of 25–30 tons per hectare achieved by nucleus estates. This occurs even though most farmers use similar types of commercial seeds and chemical fertilizers. Such findings imply that other, non-technical factors play a critical role in determining production efficiency. Socioeconomic variables, such as education, farming experience, access to extension services, and household income, are particularly salient, as they influence how farmers make decisions and manage resources rationally.

Previous studies offer diverse insights into the determinants of technical efficiency in the agricultural sector. Using the Stochastic Frontier Analysis (SFA) approach, DeLay et al. (2022) and Zewdie et al. (2021) demonstrate that inefficiency often stems from farmers' limited knowledge and managerial capacity to optimize input use. Similarly, Córdoba-Balcells et al. (2025) and Tatis Diaz et al. (2022) find that socioeconomic factors such as age, education, and experience significantly affect efficiency across various agricultural commodities in Latin America. In the Southeast Asian context, Allasiw et al. (2023) and Sofiyanti and Marampa (2025) reveal that formal education and participation in farmer groups significantly enhance technical efficiency through social learning mechanisms. Furthermore, Abdul et al. (2022) emphasize that the presence of extension services and institutional support substantially reduces inefficiency, particularly in perennial crops such as coffee and oil palm.

Research in Indonesia shows comparable patterns, though shaped by different social and institutional contexts. Chaira et al. (2024) and Jamhari et al. (2025) identify age and farming experience as significant factors influencing the technical efficiency of oil palm farmers in Jambi, while educational attainment does not always exhibit a positive correlation. Amrullah et al. (2025) and Rokhani et al. (2021) highlight that access to extension services and market information plays a vital role in reducing efficiency gaps among smallholders. Meanwhile, Prihadyanti and Aziz (2023) and Wardhiani et al. (2023) observe that farmers who are members of cooperatives or engaged in partnership schemes with companies tend to be more efficient due to improved access to technology and technical assistance. However, in areas with weak institutional support, such as among independent smallholders, efficiency levels tend to decline despite relatively high input use.

From a sociological perspective, recent literature on technical efficiency broadens the understanding of how social structures shape farmers' economic behavior. Through the livelihood approach, Chuong (2024) and He and Ahmed (2022) emphasize the role of human and social capital as key determinants of farmers' livelihood strategies. Mokhtarzadeh et al. (2021)

and Yang et al. (2022) similarly note that social networks function as crucial knowledge channels that influence production practices and decision-making. In more context-specific studies, Baka et al. (2024), Ismail et al. (2025), and Nurliza and Fauyan (2021) show that in the oil palm sector, social ties, farmer group membership, and trust in local institutions indirectly enhance efficiency through knowledge diffusion. This perspective is further supported by Santoso et al. (2023) and Syafrial et al. (2024), who find that farmers with broader social networks are better able to access technical information, market prices, and agronomic innovations, ultimately leading to higher productivity.

Methodologically, previous studies have widely adopted Stochastic Frontier Analysis to measure technical efficiency across agricultural contexts. Bibi et al. (2021) and Workneh and Kumar (2023) describe this model as one that separates random errors from inefficiency in the production process. Chaovanapoonphol et al. (2022) and Teetranont and Autchariyapanitkul (2024) extend the approach by proposing more flexible production function specifications. Later studies, such as Kusumaningsih (2023) and Oumer et al. (2022), develop applications like Frontier 4.1 and employ the one-step estimation method to identify socioeconomic determinants of inefficiency. In the case of oil palm, Đokić et al. (2022) apply the model to evaluate smallholder efficiency, finding significant interregional variation depending on local social and institutional factors.

Nevertheless, most prior research has treated socioeconomic variables as auxiliary rather than central elements of efficiency analysis. Excessive focus on technical inputs, such as fertilizer, seeds, and labor, tends to overlook the social processes, educational backgrounds, and information access that shape farmers' capacity to use inputs efficiently. In reality, many smallholders face structural barriers, including limited access to extension services, weak market networks, and dependence on informal sources of information. When these social dimensions are not systematically integrated, our understanding of technical efficiency remains incomplete, trapped within a mechanistic view of production.

This study emerges from the recognition that smallholder technical efficiency is not merely the outcome of interactions among land, fertilizer, and labor but also reflects farmers' socioeconomic capacities in resource management and decision-making. In Dolok Masihul, where most farmers operate independently without cooperative or corporate partnerships, social factors such as experience, education level, and participation in extension programs become particularly critical. The present research integrates rigorous econometric modeling with sociological insights into farmers' behavior and community structures. Accordingly, it seeks not only to measure efficiency in a mathematical sense but also to interpret how social conditions shape that efficiency.

This approach reflects an effort to shift the paradigm of efficiency analysis from purely input-based models toward a more comprehensive and human-centered understanding. When technical efficiency is viewed as the outcome of dynamic social processes, productivity-enhancing strategies must also prioritize human capacity building, through education, training, and the development of farmer knowledge networks. This is the conceptual direction proposed by the present study: that understanding and improving the technical efficiency of smallholder oil palm farmers ultimately entails rebuilding the relationship between people, knowledge, and production.

Therefore, this study aims to analyze the socioeconomic factors influencing technical efficiency among smallholder oil palm farmers in Dolok Masihul District, North Sumatra. Specifically, it seeks to (a) measure the level of technical efficiency, (b) identify the socioeconomic determinants underlying efficiency variation among farmers, and (c) provide evidence-based policy recommendations emphasizing the importance of strengthening human and social capital as strategies for productivity improvement. By adopting this approach, the study intends to make both a theoretical contribution to socially oriented efficiency literature and a practical contribution to sustainable smallholder agricultural policy in Indonesia.

RESEARCH METHOD

This study employed a quantitative approach with an explanatory research design aimed at analyzing the causal relationship between socioeconomic factors and the technical efficiency levels of smallholder oil palm farmers in Dolok Masihul District, Serdang Bedagai Regency, North Sumatra. The quantitative approach was chosen for its ability to objectively measure the contribution of variables affecting production efficiency while enabling hypothesis testing through measurable econometric models. The explanatory design was adopted to explain how farmers' socioeconomic characteristics influence technical inefficiency rather than merely describing efficiency levels. Thus, this research focuses not only on how efficient farmers are in utilizing available resources but also on why and how socioeconomic differences generate variations in efficiency.

The study utilized primary data collected through a field survey involving 125 smallholder oil palm farmers, randomly selected using a simple random sampling technique from the population of independent farmers in Dolok Masihul. The area was purposively selected because its farmers operate independently, without membership in cooperatives or corporate partnerships, making it highly relevant for examining socioeconomic factors influencing efficiency without external institutional interventions. Respondents were required to have managed oil palm farms independently for at least five years and owned land ranging from one to five hectares.

Data were collected using a structured questionnaire developed based on theoretical frameworks of technical efficiency and farmers' socioeconomic characteristics. The questionnaire consisted of two main sections. The first section gathered information on production inputs and outputs, including land size (hectares), fertilizer use (kilograms per year), labor (man-days per year), and seed type (improved or non-improved). Output data were measured by the volume of fresh fruit bunches (FFB) produced per hectare per year. The second section covered socioeconomic variables hypothesized to influence technical inefficiency, such as farmer age (years), formal education level (years of schooling), farming experience (years), number of dependents, household income (Indonesian Rupiah per month), and access to agricultural extension services (frequency of participation in extension activities during the past year). Additional data were obtained through field observations and short interviews to ensure the validity of respondents' information.

For the analysis of technical efficiency, this study applied the Stochastic Frontier Analysis (SFA) approach using the Cobb–Douglas production function model (Mbah & Agu, 2024; Obalola et al., 2025). This model was selected for its simplicity in capturing the relationship between agricultural inputs and output while allowing the separation of two sources of production variation, random error and technical inefficiency. The general form of the Cobb–Douglas production function used in this study is expressed as:

$$\ln Y_1 = \beta_0 + \beta_1 \ln X_{1i} + \beta_2 \ln X_{2i} + \beta_3 \ln X_{3i} + \beta_4 \ln X_{4i} + \nu_i - \upsilon_i \quad (1)$$

where Y_1 denotes production output (FFB per hectare), X_{1i} to X_{4i} represent production inputs (land area, fertilizer, labor, and seed type, respectively), ν_i is the random error term assumed to follow a normal distribution $N\ (0, \sigma_v^2)$, and υ_i is the technical inefficiency term assumed to follow a half-normal distribution $|N\ (0, \sigma_v^2)|$.

To identify the socioeconomic determinants of technical inefficiency, a one-step estimation approach was adopted, where socioeconomic variables were directly estimated against the inefficiency component υ_i. This approach is considered superior to the two-step method as it avoids bias that may arise from separating the estimation of efficiency and its determinants. The socioeconomic variables included in the model comprised education, farming experience, age, household income, extension access, and number of dependents. Parameter estimation was conducted using the Maximum Likelihood Estimation (MLE) method, employing Frontier 4.1 and STATA software (Ali et al., 2024).

Before estimation, data validation and consistency checks were carried out in several stages. First, data cleaning was performed to identify incomplete or illogical entries, such as extreme discrepancies between land size and production volume. Second, multicollinearity tests among input variables were conducted using the Variance Inflation Factor (VIF) to ensure no strong linear relationships among independent variables. Third, heteroskedasticity and residual normality tests were performed to validate the regression model. These steps ensured that the estimated technical efficiency accurately reflected the real conditions of smallholder oil palm farmers rather than being distorted by biased data.

The interpretation of results involved two main stages. The first stage estimated each farmer's technical efficiency score, representing how closely they approach the production frontier, with scores ranging from 0 to 1. Values approaching 1 indicate that farmers operate nearly optimally given their available resources. The second stage analyzed the socioeconomic factors contributing to variations in inefficiency among farmers. The findings were then contextualized within the social and institutional conditions of Dolok Masihul, allowing for a deeper understanding of the social dimensions of technical efficiency.

This study acknowledges several limitations. First, since the data are cross-sectional, the analysis cannot capture changes in technical efficiency over time. Second, institutional variables, such as farmers' relationships with middlemen or financial institutions, were not deeply explored, even though they may significantly influence production behavior. Third, the efficiency scores obtained are relative to the sample and should not be generalized to all Indonesian smallholder oil palm farmers without contextual caution. Nevertheless, this study provides valuable insights into how socioeconomic factors shape technical efficiency among smallholder oil palm farmers, particularly in regions with limited institutional support such as Dolok Masihul.

RESULTS AND DISCUSSION

Overview of Technical Efficiency among Smallholder Oil Palm Farmers

The analysis of technical efficiency among smallholder oil palm farmers in Dolok Masihul District provides important insights into the extent to which farmers can transform various inputs, such as fertilizers, labor, and herbicides, into output in the form of fresh fruit bunches (FFB). Based on the stochastic frontier estimation using the Maximum Likelihood Estimation (MLE) method, the average technical efficiency was found to be 0.78. This value indicates that, on average, farmers operate at 78% of their potential efficiency, implying a possible 22% increase in output without additional input use. In other words, improved management and farm practices could raise production by nearly one-fifth solely through enhanced efficiency (Rikkonen et al., 2025).

Conceptually, technical efficiency reflects the farmer's ability to optimally utilize production factors to achieve maximum output. Efficient farmers are able to minimize waste, maintain proportional input combinations, and adapt to local agroecological conditions (Goel & Vishnoi, 2025). However, in the smallholder plantation context, particularly in oil palm cultivation, efficiency extends beyond mere input–output calculations, it also involves social capacity, practical knowledge, and cognitive adaptability in managing available resources (Zhang et al., 2025).

The results revealed that technical efficiency scores among smallholders in Dolok Masihul varied between 0.55 and 0.99, indicating a wide gap across farmers. Only about 12% of respondents operated near the efficiency frontier (scores > 0.90), while the majority remained below this level. This disparity is likely driven by differences in farming experience, educational attainment, and access to agricultural training and information services.

Table 1 Distribution of Technical Efficiency among Smallholder Oil Palm Farmers in Dolok Masihul

Farmer Characteristic	Category	Mean Technical Efficiency	Key Observation
Age	30–39 years	0.73	Technically adaptive but limited in practical skill
	40–49 years	0.80	Most efficient; productive age with mature experience
	50–59 years	0.75	Declining efficiency due to physical constraints and conservative practices
Education	No schooling/Primary	0.72	Limited in adopting new technologies
	Junior–Senior High	0.79	Moderately adaptive to extension recommendations
	Diploma–Bachelor	0.88	More rational in cost and input management
Farming Experience	<10 years	0.70	Inefficient due to limited risk management experience
	≥10 years	0.82	More efficient; experience fosters technical intuition
Farm Size	1–3 ha	0.77	Small-scale, labor-constrained
	>3 ha	0.81	Larger scale allows labor and equipment efficiency

Source: Primary data processed, 2025

As shown in Table 1, the highest efficiency level was achieved by farmers aged 40–49 years, with an average score of 0.80. This age group represents the peak of physical and cognitive productivity, experienced yet still open to innovation. Farmers aged 30–39 years tend to be more adaptive to technology but lack empirical skill, whereas those aged 50 and above tend to maintain conventional practices.

Education also plays a critical role in efficiency. Farmers with higher education (Diploma or Bachelor's degree) achieved an average efficiency of 0.88, indicating their superior ability to manage information, interpret technical recommendations, and make rational economic decisions. This aligns with findings by Ihou and Mansingh (2025) and Lei and Yang (2025), who observed that education broadens farmers' perspectives and enhances their ability to adopt agricultural innovations. Conversely, less-educated farmers often rely on inherited practices that may not align with sustainable cultivation principles.

Similarly, farming experience significantly affects efficiency. Farmers with over ten years of experience achieved an average efficiency of 0.82, compared to 0.70 among those with less experience. Long-term experience enables farmers to better understand production cycles, detect plant stress symptoms, and optimize fertilizer use and harvesting schedules (Agrahari et al., 2021; Nakachew et al., 2024).

Overall, the empirical results show that most smallholders operate below the efficiency frontier, despite using adequate amounts of physical inputs such as fertilizers and labor. This suggests that inefficiency is not primarily due to input scarcity but rather to suboptimal input management. For instance, inconsistent fertilization schedules or delayed harvesting, often due to labor shortages, reduce productivity.

As Dwyer (2022) notes, productivity and well-being are not determined solely by resource availability but by the capacity to convert resources into valuable functions. In this context, technical efficiency represents not only farmers' physical ability to manage land but also their cognitive, social, and institutional capacities to optimize its use. Low efficiency thus signals limited capability rather than mere input deficiency.

In Dolok Masihul, around 50% of farmers had never attended agricultural training, leaving them uninformed about recent cultivation techniques or Good Agricultural Practices (GAP). Lacking such knowledge, farmers tend to imitate traditional methods without understanding their scientific rationale. This underscores that technical efficiency is deeply intertwined with knowledge access and social learning, not just economic calculation. As Shaikh et al. (2023) argue, capabilities represent "the real freedom to achieve valuable beings and doings", in this case, the freedom and ability to implement effective, sustainable farming practices.

Production Inputs and Output: Between Economic Rationality and Structural Constraints

The estimation of the Cobb–Douglas production function provides an empirical understanding of the relationship between production inputs and FFB output among smallholder farmers in Dolok Masihul. The results show that land size and fertilizer use significantly and positively affect production, while labor and seed type exhibit moderate or statistically insignificant effects. The model demonstrates a satisfactory goodness of fit with an R^2 of 0.68, indicating that most of the variation in output can be explained by input variation. However, beyond these figures lies a complex socio-economic reality that requires a deeper understanding of how farmers perceive and utilize resources within production systems that are both technical and social.

Table 2 Estimation Results of the Cobb–Douglas Production Function for Smallholder Oil Palm Farmers in Dolok Masihul

Input Variable	Regression Coefficient	t-Statistic	Significance	Interpretation
Land size (ha)	0.432	5.12	0.000*	Significant positive effect on production
Fertilizer (kg/ha)	0.271	3.84	0.001*	Significant positive effect on production
Labor (man-days)	0.118	1.56	0.122	Positive but not significant
Seed type (dummy: improved = 1)	0.064	0.98	0.329	Weak positive effect
Constant R^2 = 0.68	0.451	,	,	,

Source: Primary data processed, 2025

The findings indicate that land size is the most dominant factor in increasing production: a 1% increase in land area raises output by 0.43%, assuming other inputs remain constant. This supports classical production theory, which posits a positive correlation between land scale and productivity, as larger areas enable more systematic management and labor efficiency (Chen et al., 2022). However, in Dolok Masihul, most farmers cultivate only 1–3 hectares independently, without institutional support. Limited capital often leads to delayed fertilization or pruning due to financial and labor constraints, thus hindering optimal efficiency.

Fertilizer use also shows a significant effect, with an elasticity of 0.27, suggesting that a 1% increase in fertilizer use boosts output by 0.27%. Yet, this relationship is not purely linear in practice. Many farmers apply fertilizers based on habit rather than extension recommendations, often without standard dosage records. For example, a 47-year-old farmer reported measuring fertilizer “by the sack,” rather than through soil analysis. This reflects that fertilizer use is both an economic and social decision, shaped by traditions, perceptions, and peer networks.

Conversely, labor and seed type show no significant effects, indicating structural constraints within smallholder production systems. Survey data revealed that 83% of labor used came from farmers’ own households rather than hired workers. While family labor reduces costs, it often results in irregular work schedules and inconsistent farm maintenance. Household members’ competing economic activities, such as trading or wage labor, delay tasks like pruning or fertilization. Hence, farmers’ economic rationality does not always align with technical efficiency, as labor decisions are governed by household social dynamics rather than marginal profit considerations.

A similar pattern appears in seed use. Although improved seeds theoretically promise higher yields, the estimated coefficient (0.064) was weak and statistically insignificant. Field evidence suggests that most farmers use mixed seeds, combining improved and informal market varieties. Farmers often prefer market seeds for their affordability and availability despite uncertain genetic quality. Thus, seed selection is shaped not only by productivity calculations but also by economic accessibility and informational constraints.

These findings are consistent with studies by Khatiwada et al. (2021) and Tapia et al. (2021), which report that while land and fertilizer significantly enhance oil palm productivity, the contribution of labor and improved seeds is often constrained by limited skills and technical support. Similarly, Mehraban et al. (2021) and Utomo et al. (2023) found that productivity among smallholders in West Kalimantan depends less on physical inputs than on farmers’ managerial capacity to allocate labor and maintain crops effectively. Social factors such as farmer group leadership, labor solidarity, and information networks play crucial roles in explaining efficiency variations at the micro level.

This interplay between technical and social factors can be understood through the Rural Production System Theory proposed by Ruml and Qaim (2021), which emphasizes that rural agricultural production systems cannot be viewed as purely economic entities but rather as socially embedded systems linked to household structures, labor relations, and local norms.

According to Fischer and Qaim, farmers' input-use decisions are shaped by household production logic, in which production aims not only to maximize profit but also to ensure household stability and long-term sustainability. In Dolok Masihul, therefore, the use of family labor or mixed seeds should not be interpreted as "economic errors" but as social adaptations to capital constraints, market risks, and price uncertainty.

The Cobb–Douglas estimation thus reveals more than a mathematical relationship between inputs and output, it exposes the social structures underlying farmers' economic decisions. The weak statistical significance of labor does not imply its unimportance but reflects its multifunctional role within farming households, as a source of income, asset protection, and familial responsibility. Similarly, the choice of mixed seeds is not purely technical but socially conditioned by trust networks and local seed markets.

Therefore, smallholder farmers' economic rationality is contextual and socially embedded. In many cases, they adopt strategies that are "sufficiently efficient" rather than "maximally efficient," as these are socially and economically safer. As Petri et al. (2024) argue, smallholders often operate under dual rationalities, balancing economic needs with social reproduction, which may appear inefficient from a formal economic standpoint but, in reality, represent a pragmatic adaptation to risk and livelihood sustainability.

Socioeconomic Determinants of Technical Inefficiency

Based on the estimation results of the inefficiency model using the Cobb–Douglas Stochastic Frontier Analysis (SFA) approach, three socioeconomic variables, farming experience, education level, and access to agricultural extension services, were found to significantly reduce technical inefficiency. Conversely, age and number of household dependents showed no significant effects. These findings suggest that farmers' ability to manage limited resources and enhance productivity is not determined solely by demographic characteristics but rather by their knowledge capacity, experiential skills, and social embeddedness within the local agricultural ecosystem.

Table 3 Estimation Results of the Technical Inefficiency Model for Independent Oil Palm Farmers in Dolok Masihul

Socioeconomic Variable	Coefficient	t-Statistic	Significance
Farming experience (years)	-0.215	3.42	0.001
Education level (years of schooling)	-0.178	2.89	0.004
Access to agricultural extension	-0.234	3.67	0.000
Farmer's age (years)	0.037	1.12	0.264
Number of dependents (persons)	0.019	0.97	0.332

Source: Primary data processed (2025)

Negative coefficients on farming experience, education, and access to extension services indicate that improvements in these variables reduce the level of technical inefficiency, thereby enhancing production efficiency among smallholder oil palm farmers. This suggests that technical efficiency is shaped not only by the quantity of physical inputs but also by farmers' social and cognitive capacities in managing those inputs effectively.

First, farming experience proved to be a critical factor in lowering inefficiency. Farmers with longer experience possess superior skills in recognizing production patterns, managing climatic uncertainties, and optimizing the use of fertilizers and labor. Prolonged exposure to farming practices enables the development of tacit knowledge, practical, experience-based knowledge that is often undocumented but crucial for decision-making (DeLay et al., 2022; Zewdie et al., 2021). In Dolok Masihul, most farmers have cultivated oil palm for more than 15 years, allowing them to adapt to fluctuations in fertilizer prices, FFB market conditions, and seasonal productivity. Consequently, farming experience contributes not only to technical proficiency but also to adaptive capacity, the ability to adjust to structural and economic challenges (Dwyer, 2022; Shaikh et al., 2023).

Second, formal education significantly contributes to reducing technical inefficiency. Farmers with higher education exhibit stronger agrarian literacy, enabling them to better comprehend technical information on fertilizer dosage, harvesting schedules, and farm financial management. This finding aligns with Bibi et al. (2021) and Teetranont and Autchariyapanitkul (2024), who found that education enhances farmers' ability to absorb innovations and implement sustainable cultivation practices. In Dolok Masihul, where many farmers have only completed primary education, comprehension of technical recommendations from extension agents remains limited. Farmers with secondary education tend to maintain production records, calculate input–output ratios, and evaluate productivity regularly. Education thus forms the foundation of agricultural literacy, allowing farmers to make rational production decisions based on information rather than inherited habits (Agrahari et al., 2021; Nakachew et al., 2024).

Third, access to agricultural extension services exhibits the strongest effect in mitigating technical inefficiency. Extension functions as a mechanism of knowledge diffusion, facilitating information and skill exchange between farmers and agricultural institutions. Within the framework of the Knowledge Diffusion and Learning Networks theory, extension is seen as part of a social learning network in which farmers engage in interactive exchanges rather than one-way information transfer. In Dolok Masihul, farmers who regularly attend extension programs or actively participate in farmer groups demonstrate higher efficiency than those who operate independently. Extension activities also reinforce farmers' social embeddedness, their social attachment within community networks that promotes collective decision-making, information sharing, and cooperative practices (Ruml & Qaim, 2021).

Conversely, age and household size do not significantly affect technical efficiency. Older farmers, although more experienced, often face physical constraints and are less inclined to adopt new technologies. Meanwhile, family dependents in Dolok Masihul are generally involved in non-agricultural income activities such as petty trade or wage labor, limiting their contribution to farm operations. Therefore, passive demographic variables such as age and family size exert minimal influence compared with factors directly linked to knowledge capacity and social interaction.

These findings affirm that technical efficiency is a social phenomenon, not merely a result of physical input optimization. From the perspective of Knowledge Diffusion and Learning Networks, efficiency emerges from social processes that occur through interaction, learning, and information exchange among farmers (Agrahari et al., 2021; Nakachew et al., 2024). Farmers embedded within knowledge networks are better positioned to improve cultivation practices and minimize technical errors, as they operate within dynamic learning communities rather than in isolation. As Ruml and Qaim (2021) emphasize, the successful adoption of agricultural innovation often depends more on social trust and interaction than on mere technological access.

In broader terms, these results strengthen the argument that improving smallholder oil palm farmers' technical efficiency cannot rely solely on input-based interventions such as fertilizer subsidies or infrastructure improvement. Sustainable gains in efficiency require investment in human capital (education and training) and social capital (networking and trust). Human capital fosters cognitive and managerial competence, while social capital facilitates knowledge diffusion through community networks (Ali et al., 2024). Thus, smallholder development policies should prioritize community-based extension systems, nonformal agricultural education, and farmer group formation as hubs for knowledge exchange and collective learning.

Technical Efficiency as a Social Phenomenon: A Socio-Econometric Perspective

Empirical evidence from Dolok Masihul underscores that technical efficiency among smallholder oil palm farmers cannot be understood merely as an optimal combination of physical inputs and outputs. Beneath the econometric figures lies a complex web of social processes that shape how farmers manage resources, make decisions, and interact within smallholder systems. Technical efficiency, therefore, is not a purely technical construct but a social manifestation rooted in relational networks, knowledge structures, and shared values that influence economic behavior. The socio-econometric approach employed in this study integrates econometric and sociological perspectives to demonstrate that economic behavior is always socially embedded (Beckert, 2021).

The analysis revealed significant variation in efficiency among farmers despite relatively homogeneous agroecological conditions. With an average technical efficiency of 0.78, some farmers reached levels close to 0.95, while others remained around 0.60. These differences reflect not only variation in input use but also disparities in social capital, education, and information access. Farmers with broader social networks, connected to extension agents, traders, and peers, demonstrated greater ability to access price information, updated agronomic practices, and pest control strategies. Conversely, isolated farmers often delayed innovation adoption, resulting in inefficiency.

Table 4 Average Technical Efficiency by Education and Social Network Access

Farmer Category	Average Technical Efficiency
Primary education, not in farmer group	0.68
Primary education, in farmer group	0.75
Secondary education, not in farmer group	0.79
Secondary education, in farmer group	0.84
Higher education, active in extension networks	0.90

Source: Primary data processed (2025)

The table illustrates that improvements in efficiency are associated not only with formal education but also with social participation in knowledge networks. Farmers with primary education who participate in farmer groups achieve efficiency levels comparable to those with secondary education, indicating that learning by interaction can complement or even substitute for learning by schooling. Social relationships thus serve as a key medium for agrarian knowledge transfer. This finding aligns with the Socio-Economic Embeddedness Theory, which posits that economic action is inseparable from the social relations within which it occurs. Farmers in Dolok Masihul act not merely as rational economic agents but as community members bound by norms of cooperation, mutual trust, and collective knowledge exchange.

Moreover, peer learning or horizontal knowledge exchange among farmers plays a critical role in enhancing efficiency. Through daily interactions in plantations, informal meetings, or farmer group discussions, farmers share experiences regarding fertilizer dosage, pruning techniques, and pest detection. This form of learning is inherently social, driven not by formal instruction but by mutual trust and recognition of peers' practical expertise. As Beckert (2021) argues, economic actions are embedded in social orders that shape perceptions of value and risk. In the context of oil palm farming, decisions to adopt innovations are shaped not only by cost–benefit logic but also by cultural norms and interpersonal trust.

For instance, the effectiveness of agricultural extension often depends on the quality of social relationships between farmers and extension agents. In Dolok Masihul, extension programs tend to succeed when agents are perceived as part of the community rather than as external authorities. This supports the notion that technical efficiency is socially mediated, depending on relational trust and social cohesion rather than mere technological transfer. Ruml and Qaim (2021) similarly highlight that smallholder production systems rely heavily on the interplay between technical factors and household social structures.

In this context, social capital functions as a bridge between technical knowledge and practical implementation. High levels of social capital enable farmers to share risks, exchange resources, and expand access to market information. As noted by Goel and Vishnoi (2025), rural social networks serve as informal institutions that facilitate information exchange and cooperative action. In Dolok Masihul, farmers active in group-based organizations demonstrate higher efficiency due to easier access to fertilizer recommendations, subsidized input prices, and coordinated harvesting practices. Technical efficiency thus emerges as a collective outcome of social capital operating within community structures.

However, social structures can also impose constraints. Not all social networks are inclusive; some farmer groups remain closed to external ideas, thereby reinforcing social conservatism that hinders innovation adoption. This duality of embeddedness, both enabling and restrictive, illustrates how community norms can simultaneously foster cooperation and perpetuate traditionalism (Beckert, 2021). For example, some Dolok Masihul farmers continue to use uncertified local seeds despite recognizing the benefits of certified varieties due to social pressure not to deviate from community norms.

From a socio-econometric perspective, the technical efficiency model employed here effectively captures the “social trace” of farmers’ economic behavior. Variables such as education, experience, and extension access represent not only individual characteristics but also indicators of farmers’ connectedness to surrounding knowledge networks and institutions. In this sense, the Cobb–Douglas production function serves as a formal framework to map output variation, while the inefficiency model acts as a social lens revealing the human interactions underlying those figures. This interdisciplinary approach allows for a reinterpretation of quantitative data within a broader social context where economy and society are co-constitutive rather than separate domains.

Conceptually, this perspective yields three key implications. First, technical efficiency should be viewed not merely as an individual productivity measure but as an indicator of social cohesion and the effectiveness of local institutions. Second, efficiency-enhancing policies must integrate socio-cultural dimensions, such as building trust between farmers and extension agents, strengthening farmer organizations, and creating spaces for horizontal knowledge exchange. Third, future agricultural efficiency research should adopt interdisciplinary methodologies, combining statistical modeling with social ethnography, to better capture the underlying dynamics of knowledge, trust, and collective learning often hidden behind quantitative data.

CONCLUSION

This study concludes that the technical efficiency of independent oil palm smallholders in Dolok Masihul cannot be explained solely by the combination of production inputs such as land, fertilizer, or labor. Rather, it is primarily shaped by the quality of farmers’ social capacity and knowledge capital. The estimation results indicate that farming experience, educational attainment, and access to agricultural extension services play significant roles in reducing inefficiency. This finding underscores that learning, social interaction, and agrarian literacy constitute the foundation of farmers’ economic rationality. With an average technical efficiency score of 0.78, there remains a potential productivity gain of approximately 22% if resources are managed more optimally through improved managerial capacity and more equitable knowledge diffusion. These findings affirm that technical efficiency is a socially embedded phenomenon, situated within networks of interaction, community norms, and rural institutional capacities, rather than merely a technical or agronomic issue. Through a socio-econometric approach, this study broadens the understanding of smallholder productivity by placing the social dimension at the center of analysis. It recommends that rural development policies prioritize the strengthening of human capital and community-based extension systems as strategic levers to promote both economic productivity and social sustainability within the independent smallholder oil palm sector.

ETHICAL STATEMENT AND DISCLOSURE

This study was conducted in accordance with established ethical principles, including informed consent, protection of informants' confidentiality, and respect for local cultural values. Special consideration was given to participants from vulnerable groups to ensure their safety, comfort, and equal rights to participate. No external funding was received, and the authors declare no conflict of interest. All data and information presented were collected through valid research methods and have been verified to ensure their accuracy and reliability. The use of artificial intelligence (AI) was limited to technical assistance for writing and language editing, without influencing the scientific substance of the work. The authors express their gratitude to the informants for their valuable insights, and to the anonymous reviewers for their constructive feedback on an earlier version of this manuscript. The authors take full responsibility for the content and conclusions of this article.

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