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TECHNICAL EFFICIENCY AND TECHNOLOGY GAP OF SMALLHOLDER OIL PALM FARMERS: ISPO AND NON-ISPO IN RIAU, INDONESIA, USING A STOCHASTIC META-FRONTIER APPROACH

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ABSTRACT

This study examined how smallholder oil palm plantations in Indonesia's Riau Province were affected by Indonesian Sustainable Palm Oil (ISPO) certification in terms of technical efficiency and technological gaps. Data were collected from July 2023 to February 2024 from 177 farmers (87 ISPO-certified and 90 non-certified) in Siak District. The technical efficiency and technology gap ratios were estimated using the Stochastic Meta-Frontier (SMF) technique, considering the technological heterogeneity among the farmer groups. Results revealed that production among ISPO-certified farmers was significantly influenced by chemical fertilizer use, tree age, and interactions between land size and tree age, as well as between tree age and organic fertilizer application. Non-certified farmers' production was affected by tree age, labor input, chemical fertilizers, and interactions between tree age and chemical fertilizers. ISPO-certified farmers demonstrated higher technical and meta-technical efficiency, indicating more optimal input use and closer adherence to the best-practice production frontier. Technology gap ratios below one for both groups highlighted the potential for further technological improvements. These findings provide empirical evidence that ISPO certification enhances resource use efficiency and supports sustainable management practices among smallholder oil palm farmers, providing insightful information to extension services and policymakers looking to increase sector sustainability and productivity.

Key words: Indonesian Sustainable Palm Oil, input allocation

INTRODUCTION

The palm oil sector is a vital component of Indonesia's agricultural economy, making a substantial contribution to both regional and national economic expansion. According to Statistics Riau Province (2025), 83% of Indonesia's total non-oil and gas export revenue came from palm oil exports in 2021, which totaled over USD 35 billion. In addition to its macroeconomic contributions, the industry provides for the livelihoods of more than 17 million people and, thanks to the mandated biodiesel policy, is essential to the country's energy security. This highlights the crucial role that palm oil plays in socioeconomic elements and solidifies Indonesia's dominance as the world's top palm oil producer.

The amount of palm oil produced nationwide has been steadily increasing, and in 2023 it reached 47.08 million tons, up 0.57% from the year before. The five leading producing provinces, including Riau, contribute approximately 68.02% of the national production. Riau Province holds a strategic position with a production volume of 9.24 million tons, representing 19.59% of the national output, and a plantation area spanning 3.04 million hectares (Statistics Indonesia 2024). Most palm oil plantations in Riau are managed by smallholder farmers, who control 67.28% of the total plantation area (2.28 million hectares) and contribute 57.03% (5.26 million tons) of production. The remainder is managed by large private companies (30.50%) and state-owned plantations (2.22%) (Statistics Riau Province 2025). Palm oil is the preferred commodity among farmers in Riau due to its relatively higher profitability than alternatives such as rubber and coconut. The transition from rubber to palm oil reflects farmers' adaptation to market dynamics and agricultural development policies (Riau Plantation Office 2021). Data indicate that approximately 830,038 smallholder households cultivate palm oil, with an average annual income of IDR 46 million, significantly higher than those in rubber and coconut farming.

Nonetheless, the smallholder palm oil sector faces several challenges that hinder productivity and sustainability. Smallholders in Riau encounter constraints such as limited access to capital, low adoption of agricultural technologies, and suboptimal input management. Factors including technological changes, technical efficiency, farm scale, and plantation age structure are key determinants of productivity. Smallholder productivity in Riau remains relatively low, averaging only 3,183 kg/ha, substantially below the productivity of large plantations (Statistics Riau Province 2025). The primary causes include inadequate implementation of Good Agricultural Practices (GAP), limited knowledge, poor access to information, technology, capital, and managerial capacity. Moreover, the industry faces increasing international pressure, particularly from the European Union, regarding environmental concerns such as deforestation and greenhouse gas emissions. These issues have triggered trade restrictions and reputational risks, highlighting the necessity of implementing more efficient and sustainable production methods.

In response to increasing international pressure and to address the issue of low productivity in smallholder palm oil plantations in Indonesia, the Indonesian government made the Indonesian Sustainable Palm Oil (ISPO) certification mandatory to promote palm oil production that is both sustainable and socially responsible (Anwar et al. 2014; Ernah et al. 2019; Apriyanto et al. 2020). The ISPO program targets smallholders by encouraging compliance with labor and environmental standards, optimizing input use, and improving plantation management practices. However, adoption among smallholders remains very low. As of mid-2021, only 760 ISPO certificates had been issued nationwide—most of them to large companies—while very few were held by smallholders. Only 19 certificates had been issued in Riau Province, covering 9,344 hectares across four districts (Riau Plantation Office 2021). Key barriers include limited knowledge and training, restricted access to capital, and the complexity of ISPO requirements, which are often difficult for self-managed smallholders to implement (Hutabarat 2017; Apriyanto et al. 2020; Majid et al. 2021).

The limited success of ISPO implementation is often attributed to a mismatch between the certification's principles and requirements and smallholders' practical realities and socio-economic conditions. Factors such as older age, low levels of formal education, limited access to capital, and insufficient technical knowledge further exacerbate the challenges of adoption (Hidayat et al. 2018; Schoneveld et al. 2019; Apriyanto et al. 2020; Majid et al. 2021). In addition, Liana et al. (2023), in a literature review, highlighted several key challenges smallholder palm oil farmers face in Indonesia regarding sustainability certification. These challenges include limited understanding of sustainability concepts—particularly Good Agricultural Practices (GAP), weak institutional capacity among farmers, perceptions that certification is only accessible to wealthier farmers due to high costs, and uncertainty regarding the tangible benefits of certification. Their findings suggest that current regulations may not fully reflect smallholders' practical conditions and constraints, indicating a need for policy adjustments to enhance adoption.

Previous studies have demonstrated that inadequate adherence to sustainability standards and suboptimal farming practices pose significant challenges to the competitiveness of smallholder farmers, highlighting the need to assess the real-world effectiveness of ISPO certification thoroughly. While several studies have investigated the economic impacts of ISPO (Hutabarat 2017; Rohdiah et al. 2019; Christiawan 2020), there remains a notable research gap regarding the technical efficiency of smallholders in implementing ISPO.

Technical efficiency, defined as maximizing output from a given set of inputs by adopting best practices (Coelli et al. 2005), is critical for enhancing productivity and sustainability in agriculture. Traditional methods for measuring technical efficiency, such as stochastic frontier analysis, typically assume homogeneous production technologies among farmers. However, this assumption is increasingly questioned in heterogeneous agricultural settings. Ignoring technological heterogeneity can result in biased efficiency estimates, especially in contexts characterized by diverse institutional, ecological, and socio-economic conditions (Battese and Rao 2002; Rao et al. 2003; Battese et al. 2004; O'Donnell et al. 2008; Huang et al. 2014). Such heterogeneity is particularly relevant for ISPO-certified and non-certified smallholders in Riau, who operate under distinct production environments.

To address these limitations, the stochastic meta-frontier (SMF) approach has been developed. The SMF method estimates a meta-frontier representing the potential production boundary across all groups, alongside group-specific frontiers that capture unique technological contexts. The Technology Gap Ratio (TGR), derived from the SMF model, measures the extent to which a group's production frontier deviates from the meta-frontier, offering valuable insights into the potential for technological improvement (Huang et al. 2014). The SMF framework has been widely applied in efficiency studies of staple crops such as maize (Ng'ombe 2017), rice (Tinaprilla 2012; Junaedi 2016), and others (Alem 2021; Miriti et al. 2021; Kosarova and Pokrivcak 2023). However, its application in the palm oil sector remains limited, with only a few studies examining technological efficiency among smallholder oil palm farmers operating independently or in partnerships (Varina et al. 2020b).

Building on this framework, the present study employs the meta-frontier approach to examine technology gaps and variations in technical efficiency between ISPO-certified and non-certified smallholder oil palm plantations in Riau Province, Indonesia. Additionally, it investigates the key factors influencing productivity among these farmers. Through this analysis, the study aims to provide a comprehensive understanding of how technological heterogeneity and differences in management practices associated with certification status affect productivity outcomes.

RESEARCH METHODOLOGY

Research location. This research was carried out in Siak District, Riau Province, Indonesia (Fig. 1), which was purposively chosen due to its status as a key area for smallholder oil palm plantations and as the province's foremost center for ISPO-certified smallholders, with 11 certificates issued at the time of the study. The diverse farming systems and certification status variations among Siak’s smallholders provide an ideal setting to analyze differences in farm management, technical efficiency, and sustainable cultivation adoption. Additionally, Siak’s socio-economic profile broadly represents oil palm smallholders across Indonesia, enhancing the study's generalizability.

Data types and sources. Primary data were collected from 177 smallholder farmers in Siak District, Riau Province, Indonesia, through field observations and structured interviews between July 2023 and February 2024. The sample included 87 ISPO-certified and 90 non-certified farmers. ISPO-certified farmers were purposively sampled based on active plantation management and a minimum of three years' certification to ensure data reliability. Non-certified farmers were selected using justified sampling, focusing on active plantation managers without ISPO or other certifications.

Secondary data from regional agricultural offices, ISPO bodies, and government reports supplemented the primary data to enhance analysis robustness.

Figure 1. Study area location map

Data analysis. This research utilized a two-stage Stochastic Meta-Frontier (SMF) method by Huang et al. (2014) to assess and compare the technical efficiency (TE) and technology gap ratio (TGR) between ISPO-certified and non-certified smallholder oil palm farmers. This method effectively accounts for heterogeneity among groups operating under varying technological environments. Data analysis was performed using STATA MP 17 software.

Stage 1: Group-specific stochastic frontier analysis. In the initial phase, stochastic production frontiers were separately estimated for two categories of smallholder oil palm farmers: those holding Indonesian Sustainable Palm Oil (ISPO) certification and those uncertified. This differentiation accounts for potential variations in production technologies and management practices between the groups, thereby enhancing the precision of technical efficiency estimations.

Using the Stochastic Frontier Analysis (SFA) framework, this stage analyzes the factors influencing production output and inefficiency levels within each group, offering insights into efficiency disparities related to certification status.

The general specification of the stochastic production frontier is:

$$Y_{ji} = f^j(X_{1ji}, X_{2ji}, X_{3ji}, \ldots, X_{nji})e^{v_{ji}-u_{ji}} \text{ ; j = farmers group} \quad (1)$$

In its logarithmic form, the model becomes:

$$\ln Y_i = \beta_0 + \sum_{j=1}^{6} \beta_j \ln X_{ji} + \frac{1}{2}\sum_{j=1}^{6}\sum_{k=1}^{6} \theta_{jk} \ln X_{ji} \ln X_{ki} + (v_i - u_i) \quad (2)$$

The production of fresh fruit bunches (FFB), denoted as Y_i and measured in kilograms per year, is modeled as a function of several inputs. These inputs include land area (X_1) measured in hectares, age of palm trees (X_2) in years, chemical fertilizer application (X_3) in kilograms per year, organic fertilizer usage (X_4) in kilograms per year, pesticide use (X_5) in liters per year, and labor input (X_6) measured in person-hours per year. The model accounts for statistical noise, represented by v_i, which is assumed to be normally distributed with mean zero and variance $\sigma^2_{v_j}$. Additionally, an inefficiency term, u_i, captures deviations from the frontier and is assumed to follow a truncated normal distribution.

The model was estimated using maximum likelihood estimation (MLE) to obtain consistent and efficient parameter estimates. A positive β signified a positive marginal impact of inputs on output, while interaction terms reflected synergistic effects between inputs, improving the explanatory capacity of the production function. The SFA model separated the composite error term into a symmetric random error (v_i), representing statistical noise arising from measurement errors and external shocks, which was assumed to be independently and identically distributed:

$$v_i \sim N(0, \sigma^2_{vj}) \tag{3}$$

Conversely, the inefficiency term (u_i) was modeled as a truncated normal distribution, capturing deviations from the frontier due to inefficiencies in management and technology:

$$u_i \sim N^+(\mu_j(Z_{ji}), \sigma^2_{uj}) \tag{4}$$

The term N^+ refers to a normal distribution truncated at zero, ensuring the non-negativity of inefficiency scores.

Inefficiency model specification. Technical inefficiency among smallholder oil palm plantations was modeled using the following equation:

$$u_i = \delta_0+\delta_{1i}Z_{1i}+\delta_{2i}Z_{2i}+\delta_{3i}Z_{3i}+\delta_{4i}Z_{4i}+\delta_{5i}Z_{5i}+\delta_{6i}Z_{6i} \tag{5}$$

Where Z_{1i} represents the age of the *i*-th farmer in years, Z_{2i} denotes formal education measured in years, and Z_{3i} indicates farming experience in years. The number of family dependents is captured by Z_{4i}, measured as the number of people. Z_{5i} is a dummy variable for farm management type, where 1 indicates partnership (plasma farmers) and 0 represents self-managed (independent farmers). Lastly, Z_{6i} is a dummy variable for ISPO certification status, with 1 indicating ISPO-certified farmers and 0 for non-certified ones.

Positive δ values indicate increased inefficiency, while negative values reflect efficiency gains. A dummy variable differentiates farm management types: self-managed (independent) and partnership-based (plasma) farmers. Partnership farmers typically have better access to inputs, technical support, and markets, potentially boosting efficiency. This classification helps evaluate how management affects performance and access to resources. This distinction is key for ISPO certification, as awareness is higher among self-managed farmers linked to farmer groups, while many independent, non-certified farmers remain unaware. Thus, management type highlights institutional gaps affecting sustainable practice adoption and certification compliance.

Technical efficiency analysis. Technical efficiency (TE) for individual smallholder oil palm farmers in a group was estimated using the following expression:

$$TE_i^j=\frac{Y_{ji}}{f^j(X_{ji})e^{v_{ji}}}=e^{-u_{ji}} \tag{6}$$

Where TE_{ji} represents the technical efficiency score of the *i*-th farmer in group *j* Y_{ji} denotes the observed output measured as fresh fruit bunch production in kilograms per year, and $f_j(X_{ji})$ refers to the deterministic component of the production function specific to group *j*. The vector X_{ji} contains the inputs the *i*-th farmer utilizes within group *j*.

Technical efficiency (TE) values range from 0 to 1, where a value of 1 represents full efficiency, indicating that inputs are used optimally to achieve maximum output. Scores below 1 reflect varying degrees of inefficiency. A TE value above 0.7 is considered relatively high (Kumbhakar and Lovell 2000). Meanwhile, technical efficiency is categorized into three levels: low (TE < 0.6), medium (TE between 0.6 and 0.8), and high (TE > 0.8) (Tanjung 2003). This classification serves as a valuable framework for assessing the performance of smallholder oil palm farmers and identifying areas in need of targeted development interventions.

Stage 2: Meta-frontier production function and technology gap analysis. To reflect the best available technology across all groups, a stochastic meta-frontier was estimated in the second step to encapsulate the group-specific frontiers. This is how the meta-frontier production function was defined:

$$f^j X_{ji} = \ln(f^M(X_{ji})) \cdot e^{-u_{ji}^M}, \forall j,i \tag{7}$$

Where, $f^M(X_{ji})$ denotes the meta-frontier production function that includes the frontiers of both ISPO-certified and non-certified farmers, implying that $f^M(X_{ji}) \geq f^j(X_{ji})$. The term $u_{ji}^M \geq 0$ reflects the inefficiency relative to the meta-frontier caused by the technological gap.

The ratio of the group-specific frontier output to the meta-frontier output was measured by the Technology Gap Ratio (TGR), which was expressed as follows:

$$TGR_i^j = \frac{f^j(X_{ji})}{f^M(X_{ji})} = e^{-u_{ji}^M}, \; 0<TGR_{ji}\leq 1 \tag{8}$$

The Technology Gap Ratio (TGR) quantified how closely farmers employed the optimal production technology. A TGR of 1 signified that farmers operated on the meta-frontier, fully adopting the sector's most efficient production methods. In contrast, a TGR below 1 reflected a technological shortfall, which led to less-than-optimal output due to restricted access to advanced production technologies. Understanding TGR is crucial for identifying opportunities to enhance productivity through improved production efficiency, including better access to modern technologies that can help reduce disparities among smallholder farmers. In this context, the term u_{ji}^M in Equation (8) represents the degree of access to or utilization of best-practice technologies.

Meta-Technical Efficiency (MTE) assessed the overall efficiency of farmers in relation to the meta-frontier by combining both input use efficiency and the degree of technology adoption. Formally, MTE was defined as:

$$MTE_i^j = \frac{Y_{ji}}{f^M(X_{ji}) \cdot e^{V_{ji}}} = TGR_i^j \cdot TE_i^j \tag{9}$$

An MTE value of 1 indicated that farmers had fully optimized production by applying best-practice technologies and efficiently utilizing resources, achieving the highest efficiency relative to the meta-frontier. Conversely, an MTE value less than 1 signified opportunities for improvement among smallholder oil palm farmers, reflecting technological inefficiencies and gaps compared to the meta-frontier.

RESULTS AND DISCUSSION

Socio-demographic profile of smallholder oil palm farmers in Riau. Table 1 compared the characteristics between ISPO-certified and non-certified smallholder farmers in Riau Province. Significant differences were observed in organizational membership and access to training, which were closely associated with certification status and farm management quality. Case evidence from Siak District showed that ISPO-certified farmers benefited from enhanced institutional support and access to information, which likely improved productivity and encouraged the adoption of sustainable practices. These findings aligned with prior research indicating that farmer organizations facilitated compliance and sustainability through better institutional access (Nuliza et al. 2019), that training and incentives increased willingness to adopt certification (Reich and Musshoff 2025), and that organizational participation often served as a prerequisite for engaging in sustainability schemes (Jelsma et al. 2024).

Table 1. Socio-demographic characteristics oil palm smallholder farmers in Riau

Soico-demographic characteristics	ISPO certified farmers	Non-ISPO certified farmers
Farmer age (years)	51.78	48.94
Education level (years)	9.59	9.10
Farming experience (years)	24.21	23.57
Family dependents (persons)	3.00	3.00
Farmers' participation in agricultural organizations	87.00	45.00
Access to agricultural training	87.00	28.00
Characteristic smallholder oil palm plantations		
Land area (hectare)	1.94	2.49
The cultivation age of oil palm trees (years)	15.67	18.49
Planting density (trees/ha)	127.00	132.00
Input use patterns		
Fertilizer (kg/ha/year)	392.90	439.88
Pesticide (liter/ha/year)	12.77	5.37
Labor (HOK/ha/year)	35.61	32.37
Productivity and selling price		
Fresh Fruit Bunches (FFB) (kg/ha/year)	18,011.64	20,243.24
Selling price (Rp/kg)	2,879.00	1,997.00

Source: primary data on the field (2024) (own survey)

Age of farmers. Most smallholder oil palm farmers in Riau Province, whether ISPO-certified or not, were within the productive age group. ISPO-certified farmers had a slightly higher average age (51.78 years) than non-certified farmers (48.94 years). While the age gap was modest, it carried social and psychological implications. Older farmers might have been more inclined toward certification due to greater farming experience and stronger social networks. However, age-related physical and cognitive decline could have limited their adaptability to technical innovations (Ngaisset and Jia 2020). Hence, targeted extension and support services were essential to facilitate the adoption of sustainable practices among ageing farmer populations.

Education level of farmers. Formal education was a critical factor influencing the adoption of sustainability certification. ISPO-certified and non-certified farmers in Riau Province had comparable average education levels—9.59 and 9.10 years, respectively—equivalent to junior high school. Although the difference was insignificant, education enhanced farmers' understanding of sustainability concepts, certification procedures, and access to modern agricultural information and technologies. Higher education also promoted engagement in training, extension services, and institutional support, all essential for farm development. Better-educated farmers were more receptive to innovation and implemented Good Agricultural Practices (GAP), thereby improving productivity and sustainability (Alwarritzi et al. 2015). Thus, continuous investment in formal and non-formal education through training and extension was vital to increasing ISPO certification uptake among smallholders.

Farming experience. Most smallholder oil palm farmers in Riau, whether ISPO-certified or not, showed considerable farming experience, with an average exceeding 23 years. This experience constituted valuable social capital, enhancing local knowledge and supporting sustainable management practices. However, experience alone did not ensure improved farm performance without complementary access to training, technological innovations, and market incentives. Thus, integrating farming experience with institutional support such as technical training and extension services was critical to translating traditional knowledge into modern practices that complied with ISPO certification standards.

Family dependents. The average household size of smallholder oil palm farmers in Riau, irrespective of their ISPO certification status, was three dependents, ranging from one to six. This suggests that household size may have influenced their participation in ISPO certification. Farmers with more dependents faced greater economic pressure, motivating them to seek additional income through certification, which offered benefits like higher fresh fruit bunch (FFB) prices and better market access. Certified farmers gained premium prices, improved competitiveness, and stronger bargaining power, encouraging certification, especially among those with larger families. However, certification costs, administrative hurdles, and technical training remained barriers. Hence, institutional support through subsidies, training, and assistance was essential to help farmers, particularly those with many dependents, complete the certification process.

Farmers' participation in agricultural organizations. Significant differences in training participation between ISPO-certified and non-ISPO farmers reflected disparities in involvement with agricultural institutions. Most ISPO farmers were members of active organizations such as farmer group associations (Gapoktan) or cooperatives that facilitated training, extension, and technical assistance. This involvement provided broader access to information, production inputs, and administrative support critical for certification and sustainable cultivation practices.

In contrast, non-ISPO farmers, especially independent smallholders, often had weak institutional ties, limiting their access to training and support. This hampered their capacity to adopt sustainable practices and meet certification standards. This aligned with previous studies highlighting the importance of institutions in certification adoption. Nuliza et al. (2019) noted that farmer organizations improved compliance and access to support. Reich and Musshoff (2025) showed that training and incentives boosted smallholders' willingness to certify, while Jelsma et al. (2024) stressed institutional participation as key for sustainability efforts. However, Najmi et al. (2019) pointed out challenges such as low education and limited institutional capacity for financing, especially in South Aceh. The perceived low benefits reduced farmers' motivation to join organizations. Thus, strengthening farmer institutions was crucial as technical-administrative support and a strategy to increase sustainable practice adoption and certification participation among smallholder palm oil farmers.

Access to agricultural training. Table 1 revealed a significant difference in training participation between ISPO-certified and non-ISPO palm oil farmers. While all ISPO farmers attended Good Agricultural Practices (GAP) training, non-ISPO farmers primarily received training only through company partnerships. This disparity reflected gaps in technical capacity and institutional access, influencing farmers' readiness to adopt sustainable practices aligned with ISPO.

Training enhanced farmers' technical, administrative, and institutional skills and was a vital channel for the diffusion of agricultural innovation (Rogers et al. 2009). According to the Diffusion of Innovations Theory, adopters ranged from innovators to laggards. Training improved knowledge in environmental management, farm record-keeping, and certification compliance, thereby increasing production efficiency (Asaad et al. 2022). It also empowered farmers to become early adopters and change agents within their communities. Institutional training delivered through cooperatives or farmer groups was more effective than individual-based approaches. These findings highlighted the importance of strengthening institutional training and extension systems to broaden ISPO certification adoption, particularly among independent non-certified farmers with limited access to information and support.

Profile of smallholder oil palm plantations in Riau. This study examined smallholder oil palm plantations in Riau Province by comparing ISPO-certified and non-certified farmers and evaluating plantation size, oil palm age, and land ownership (Table 1).

Land area. ISPO-certified farmers managed smaller plantations (an average of 1.94 ha) than non-ISPO farmers (2.49 ha), with most plantations ranging between 2 and 2.5 hectares, classified as small to medium scale. This small-scale, individually managed structure was typical in the Indonesian smallholder sector, often limiting access to technology and markets. Consequently, farmers relied heavily on external support such as replanting programs, technical assistance, financing, and partnerships with palm oil mills (PKS). Participation in farmer groups (Gapoktan) was key to disseminating ISPO certification information among smallholders in Riau.

The cultivation age of oil palm trees. The distribution of plant ages among responses indicated that ISPO-certified and non-certified farmers cultivated oil palm trees of varying ages. The average plant age for ISPO farmers was 15.67 years, while non-ISPO farmers had older plantations, averaging 18.49 years. Agronomically, plant age was a critical factor affecting oil palm productivity. Optimal production typically occurred between 7 and 18 years, peaking around 9–14 years (Tampubolon 2016). Productivity declined gradually after this period, with significant decreases usually observed after 22 years (Lubis and Iskandar 2018). Nonetheless, sound agronomic management could mitigate the adverse effects of aging trees (Risza 2009). Therefore, effective management of plant age was essential to enhance production efficiency and sustainability, particularly for farmers aiming to comply with certification standards like ISPO.

Planting density. The study revealed differences in planting density practices between ISPO-certified and non-certified farmers. ISPO-certified plantations had an average density of 127 palms per hectare, while non-ISPO plantations averaged 132 palms per hectare. Both values fell within the technical recommendations set by the Directorate General of Plantations (2014), which ranged from 125 to 150 palms per hectare. These findings aligned with previous studies by Nainggolan and Fitri (2024) in Muaro Jambi and Chaira et al. (2024) in Batanghari, which reported similar density ranges. Although higher planting densities may have offered short-term benefits through increased early yields (Chalil et al. 2023), long-term productivity depended largely on agronomic practices aligned with sustainable cultivation principles. Therefore, optimizing planting density needed to be integrated with technical standards to maintain consistent production throughout the productive lifespan of the palms.

Input use patterns. Table 1 illustrated the differences in input usage between ISPO-certified and non-certified smallholder farmers in Riau.

Fertilization. Fertilization is critical in oil palm cultivation because it directly influences vegetative and generative growth, ultimately affecting fresh fruit bunch (FFB) yields. Budiargo et al. (2015) highlighted that inadequate or imbalanced fertilization often reduces productivity among smallholders, particularly when fertilizer application does not correspond to plant nutritional requirements. Similarly, Khalida and Lontoh (2019), in their study of independent smallholders in Sungai Sagu, Riau, emphasized that efficient fertilizer management is essential for optimal plantation performance. However, it is often constrained by limited technical knowledge and financial capacity.

Findings from this study (Table 1) show that neither ISPO-certified nor non-certified farmers fully complied with the recommended fertilizer application rates established by the Directorate General of Plantations (2014). ISPO-certified farmers applied an average of 392.90 kg/ha/year, below the recommended 471.35 kg/ha/year, possibly reflecting environmentally conscious practices encouraged through certification. Non-ISPO farmers applied 439.88 kg/ha/year, slightly below the recommended 448.86 kg/ha/year.

These findings were consistent with Varina (2020a), who reported that fertilization practices among smallholders remained suboptimal nationwide, both in quantity and in accordance with plant age and nutrient requirements. Jelsma et al. (2019) further observed that independent smallholders tended to apply fertilizers in unbalanced proportions and lower quantities than scheme-linked farmers, mainly due to their limited access to agronomic guidance and market incentives. In addition, Liana et al. (2023), in their literature review, found that farmers' limited knowledge in implementing Good Agricultural Practices (GAP) was closely linked to their restricted access to affordable production inputs and inadequate transportation for fresh fruit bunches (FFB) during harvest. These structural limitations might have indirectly affected fertilization efficiency, as farmers prioritized cost and accessibility over adherence to recommended nutrient management practices.

Pesticide. ISPO-certified farmers applied more pesticides (12.77 litres/ha/year) than non-certified farmers (5.37 litres/ha/year), likely because of the mandatory Integrated Pest Management (IPM) protocols under ISPO standards. IPM required controlled pesticide use to optimize pest control while minimizing environmental impacts. Improper herbicide use in Pelalawan, Riau, was reported to have reduced productivity by damaging tree health and soil conditions (Alwarritzi et al. 2015). However, differences in pesticide use did not necessarily indicate substantial gaps in cultivation quality, as some non-certified farmers followed similar practices but faced barriers such as certification costs and limited access to information. Thus, variations in pesticide use reflected differences in standard operating procedures and access to certification, rather than fundamental disparities in management quality. These findings highlighted the need for training and information dissemination among non-certified farmers to promote effective and environmentally responsible pest control and equitable access to certification.

Labor. Labor input was slightly higher among ISPO-certified farmers, averaging 35.61 workdays/ha/year, compared to 32.37 workdays/ha/year for non-certified farmers. This difference may have reflected more intensive management practices or additional tasks required to comply with certification standards. Despite the higher labor input, such practices could have enhanced farm productivity and sustainability through improved management efficiency.

Productivity and Fresh Fruit Bunch (FFB) Selling Price. The results revealed that the average productivity of ISPO-certified farmers was 18,011.64 kg/ha/year, slightly lower than that of non-ISPO farmers, who averaged 20,243.24 kg/ha/year. Hutabarat (2018) similarly found that productivity varied among smallholders, with RSPO-certified farmers producing 20.30 tons/ha/year, non-certified farmers 15.50 tons/ha/year, and plasma-certified farmers 13.50 tons/ha/year.

However, ISPO-certified farmers received higher FFB prices (IDR 2,879/kg) than non-ISPO farmers (IDR 1,997/kg), indicating a market preference for sustainable practices. This finding aligned with Hidayat et al. (2016) and Siregar (2023), who reported premium pricing for sustainably produced palm oil. Nevertheless, buyer–farmer partnerships also influenced price formation, suggesting that the direct impact of ISPO certification on price premiums warranted further investigation. ISPO was often regarded more as a mechanism for technical and managerial improvement than as a direct price driver (Rohdiah et al. 2019), while inconsistent compliance with sustainability standards continued to limit smallholders' access to premium markets (Schoneveld et al. 2019).

Reich and Musshoff (2025) identified price incentives and market access as key drivers motivating smallholder certification, although debates regarding ISPO's market effectiveness persisted. In this context, Mustofa et al. (2025) emphasized that ISPO was critical in promoting Good Agricultural Practices (GAP) and environmental stewardship, thereby improving production standards. Conversely, Pramudya et al. (2022) argued that ISPO's strong regulatory orientation might have constrained innovation and value creation among smallholders. These contrasting perspectives suggested that, while ISPO contributed to improved farming practices, its influence on economic incentives remained ambiguous and may have varied depending on market dynamics and the quality of implementation.

Estimation of SFA Model: Factors affecting Fresh Fruit Bunch (FFB) production. In order to examine the varying effects of input variables on FFB production between ISPO-certified and non-ISPO smallholder oil palm farmers in Riau Province, this study used a Translog production function calculated by Stochastic Frontier Analysis (SFA). The findings are compiled in Table 2.

Table 2. Estimation of factors affecting fresh fruit bunch (FFB) production and inefficiency of smallholder oil palm plantations by ISPO certification status

Variables	Stage I							
	ISPO certified				Non-ISPO certified			
	Coefficients	Z	P>|Z|		Coefficients	Z	P>|Z|	
Constant	-54.301	-2.68	0.007		1.377	0.30	0.762	
lnLand (lnX_1)	-17.389	-1.15	0.251		-1.051	-0.58	0.563	
lnAge (lnX_2)	6.066	1.37	0.170		3.590	3.10	0.002	***
lnChem (lnX_3)	11.875	2.41	0.016	**	-1.787	-2.11	0.035	**
lnOrg (lnX_4)	-0.684	-1.78	0.075	*	0.094	1.17	0.240	
lnPest (lnX_5)	7.998	1.33	0.183		1.244	1.39	0.164	
lnLab (lnX_6)	7.889	1.57	0.116		3.683	2.09	0.037	**
Quadratic variables:								
lnLand ^{squared}	1.059	0.50	0.618		0.109	0.39	0.693	
lnAge ^{squared}	2.146	1.72	0.086	*	-0.642	-7.97	0.000	***
lnChem ^{squared}	-0.302	-0.76	0.445		0.309	4.45	0.000	***
lnOrg ^{squared}	0.005	0.70	0.486		0.002	1.14	0.256	
lnPest ^{squared}	0.055	0.37	0.715		0.043	1.03	0.301	
lnLab ^{squared}	0.201	0.38	0.701		0.179	0.57	0.568	
Interaction variables:								
lnLand x lnAge	6.948	2.01	0.045	**	0.069	0.35	0.723	
lnLand x lnChem	0.418	0.13	0.896		-0.266	-0.80	0.426	

Variables	Stage I							
	ISPO certified				Non-ISPO certified			
	Coefficients	Z	P>|Z|		Coefficients	Z	P>|Z|	
lnLand x lnOrg	-0.097	-0.70	0.481		-0.008	-0.40	0.687	
lnLand x lnPest	-1.259	-0.93	0.354		0.059	0.29	0.772	
lnLand x lnLabor	1.592	0.58	0.564		0.598	1.05	0.292	
lnAge x lnChem	-0.370	-0.73	0.468		0.218	3.60	0.000	***
lnAge x lnOrg	0.417	1.74	0.082	*	-0.004	-0.68	0.494	
lnAge x lnPest	-6.216	-1.93	0.054	*	-0.170	-2.19	0.028	**
lnAge x lnLab	0.053	0.09	0.930		-0.292	-1.18	0.240	
lnChem x lnOrg	0.007	0.19	0.852		-0.009	-0.93	0.351	
lnChem x lnPest	-0.080	-0.13	0.894		0.029	0.29	0.779	
lnChem x lnLab	-1.720	-2.13	0.034	**	-0.587	-1.88	0.060	*
lnOrg x lnPest	0.017	0.73	0.466		-0.008	-0.96	0.336	
lnOrg x lnLab	0.015	0.44	0.663		-0.002	-0.12	0.908	
lnPest x lnLab	0.395	0.48	0.633		-0.279	-1.30	0.194	
Inefficiency variables:								
Constant	0.098	1.63	0.104		-5.667	-2.71	0.007	
Farmer age (Z_1)	-0.005	-0.45	0.650		0.036	0.81	0.419	
Education level (Z_2)	0.002	0.04	0.965		0.018	0.23	0.822	
Farming experience (Z_3)	0.001	0.04	0.971		-0.036	-0.91	0.363	
Family dependents (Z_4)	-0.002	-0.31	0.756		-0.059	-0.28	0.777	
Management pattern dummy (Z_5)	0.007	0.41	0.683		1.162	1.91	0.056	*
Statistics model:								
Sigma_u	0.051				0.112			
Sigma_v	0.098				0.068			
Lambda	0.519				1.645			
Log likelihood	68.801				63.458			

***, **, * significant at the α levels of 1%, 5%, and 10%, respectively.
Source: Own computation using STATA/MP17.0

ISPO certified farmers. The SFA results indicated that chemical fertilizer use (ln X_3) significantly and positively influenced FFB production, with a coefficient of 11.875 ($p < 0.05$). This underscored the critical role of chemical fertilizers as primary nutrient sources supporting palm physiological processes from vegetative growth to fruit formation. These findings reinforced previous studies by Welda et al. (2020); Ariyanto et al. (2020); Mustari et al. (2020); Syuhada et al. (2022); and Jamhari et al. (2025) that highlighted the importance of fertilizer inputs in enhancing productivity and technical efficiency in oil palm cultivation. The application of organic fertilizers (ln X_4), on the other hand, had a significantly negative impact (-0.684; $p < 0.10$), which could be related to ISPO-certified farmers' inefficient usage practices and limited supply. However, in the medium and long term, organic inputs remain strategically valuable for advancing sustainable horticulture.

The squared term of plant age (ln X_2^2) had a positive and statistically significant effect on production (coefficient 2.146; $p < 0.10$), indicating a nonlinear relationship where FFB yields increase at an accelerating rate as the oil palm trees mature. This reflected the variation in plantation age phases among ISPO-certified farmers—from early production stages (3–4 years) to peak productivity (12–18 years)—highlighting the need for age-specific management strategies to optimize yield and sustainability. Significant interaction effects revealed synergistic dynamics within the production system. For example, the interaction between land area and plant age (ln X_1 × ln X_2) was positive and significant ($p < 0.05$), emphasizing effective land management during peak productive periods. Similarly, interactions between plant age and pesticide use (ln X_2 × ln X_5) and between chemical fertilizer and labor (ln X_3 × ln X_6) showed significant impacts, underscoring the importance of labor quality in enhancing the effectiveness of agronomic inputs in labor-intensive smallholder systems.

Overall, the production structure among ISPO-certified farmers was complex and nonlinear, requiring integrated input management approaches that consider input interdependencies rather than isolated input intensification. These results provide important implications for designing targeted policy and management strategies to enhance productivity and promote sustainable practices within the framework of ISPO certification.

Non-ISPO certified farmers. For non-ISPO-certified farmers, plant age (ln X_2) positively and significantly affected FFB production (coefficient 3.590; $p < 0.01$), consistent with previous studies identifying 7–18 years as the optimal productive age range (Tampubolon, 2016). Labor input (ln X_6) also had a positive impact on production (coefficient 3.683; $p < 0.05$), reflecting the essential role of manual labor due to limited mechanization.

The quadratic terms for plant age (ln X_2^2) and chemical fertilizer (ln X_3^2) were both significant but with contrasting signs: plant age squared was negative (−0.642; $p < 0.01$), indicating declining productivity beyond peak age, while chemical fertilizer squared was positive (0.309; $p < 0.01$), suggesting a nonlinear response that supports optimizing fertilizer dosage to avoid inefficiencies. Notably, the interaction between plant age and chemical fertilizer (ln X_2 × ln X_3) positively influenced production (coefficient 0.218; $p < 0.01$), highlighting the importance of age-specific fertilization strategies to maximize efficiency. Significant adverse effects were observed in some input variables and interactions—such as between plant age and pesticide use, chemical fertilizer and labor, and pesticide and labor—indicating inefficiencies likely caused by suboptimal input combinations or timing. These results underscore the complexity and nonlinearity of production processes in non-ISPO farms, paralleling ISPO-certified farms, and emphasize the need for integrated, adaptive input management to enhance productivity sustainably.

Technical inefficiency of smallholder oil palm plantations in Riau. The second stage of the Stochastic Frontier Analysis (SFA) revealed significant differences in technical inefficiency between ISPO-certified and non-ISPO smallholder oil palm farmers. For ISPO-certified farmers, the lambda (λ) value of 0.519 indicated that output deviations were primarily caused by random noise rather than inefficiency. The low inefficiency variance ($\sigma_u = 0.051$) and insignificant effects of socio-economic variables (age, education, farming experience, family dependents) suggested that ISPO certification effectively standardized cultivation practices through Good Agricultural Practices (GAP). This standardization minimized variation in farm management and reduced dependency on individual farmer characteristics, fostering more uniform and efficient production.

Conversely, for non-ISPO farmers, a higher lambda ($\lambda = 1.645$) indicated that technical inefficiency was the dominant source of output variation. The inefficiency variance ($\sigma_u = 0.112$) exceeded the stochastic error variance ($\sigma_v = 0.068$), reflecting less efficient farm operations. The significant effect of farm management patterns (dummy variable coefficient = 1.162, $p < 0.10$) highlighted that traditional, experience-based practices without formal technical support contributed to inefficiency. These results highlighted how crucial institutional support and technical guidance were to raising farm efficiency.

Overall, the analysis underscored that institutional frameworks and standardized management practices were critical in reducing technical inefficiency among smallholder oil palm farmers. Enhancing managerial capacity and promoting access to extension services and training could mitigate inefficiencies and improve productivity, especially for non-ISPO farmers.

Estimation of SMF model: Factors affecting meta-frontier production. The SMF framework thoroughly analyzed efficiency levels and technological disparities between ISPO-certified and non-ISPO farmers by estimating a meta-frontier production function that accounted for technological differences across groups. The meta-frontier production function represented the highest achievable output by integrating all group-specific production frontiers. The SMF results presented in Table 3 showed that key inputs significantly influenced the meta-frontier output in Riau's smallholder oil palm sector, with plant age and labor identified as the most influential factors.

Table 3. Stochastic meta-frontier parameter estimates for smallholder oil palm plantations in Riau

Variables	Stage II Stochastic Meta-frontier *(SMF)*		
	Coefficients	**Z**	**P>|Z|**
Constant	1.429	0.41	0.684
lnLand (lnX_1)	-0.432	-0.27	0.787
lnAge (lnX_2)	2.365	4.87	0.000 ***
lnChem (lnX_3)	-0.129	-0.18	0.861
lnOrg (lnX_4)	0.041	0.64	0.520
lnPest (lnX_5)	-0.005	-0.01	0.994
lnLab (lnX_6)	2.502	2.21	0.027 **
Quadratic variables:			
lnLand ^{squared}	0.564	2.35	0.019 **
lnAge ^{squared}	-0.529	-8.89	0.000 ***
lnChem ^{squared}	0.353	5.43	0.000 ***
lnOrg ^{squared}	0.001	0.26	0.797
lnPest ^{squared}	0.026	0.73	0.467
lnLab ^{squared}	0.673	2.84	0.005 ***
Interaction variables:			
lnLand x lnAge	0.046	0.44	0.658
lnLand x lnChem	0.352	1.23	0.219
lnLand x lnOrg	-0,010	-0,59	0,554

Variables	Stage II Stochastic Meta-frontier *(SMF)*			
	Coefficients	**Z**	**P>|Z|**	
lnLand x lnPest	-0,247	-1,51	0,132	
lnLand x lnLabor	-0,496	-1,15	0,251	
lnAge x lnChem	0,111	1,91	0,056	*
lnAge x lnOrg	-0,003	-0,91	0,364	
lnAge x lnPest	-0,001	-0,01	0,993	
lnAge x lnLab	-0,083	-0,91	0,364	
lnChem x lnOrg	-0,011	-1,23	0,220	
lnChem x lnPest	-0,024	-0,27	0,789	
lnChem x lnLab	-1,125	-3,95	0,000	***
lnOrg x lnPest	-0,003	-0,54	0,589	
lnOrg x lnLab	0,015	1,10	0,270	
lnPest x lnLab	0,054	0,43	0,667	
Statistics model:				
Sigma_u	0,113			
Sigma_v	0,086			
Lambda	1,322			
Log likelihood	105,964			

***, **, * significant at the α levels of 1%, 5%, and 10%, respectively.
Source: Own computation using STATA/MP17.0

Specifically, plant age positively influenced output (coefficient = 2.365, $p < 0.01$), consistent with agronomic literature indicating peak production around 14 years of age, followed by a decline after 22 years (Tampubolon 2016; Lubis and Iskandar 2018). Additionally, labor input significantly increased productivity (coefficient = 2.502, $p < 0.05$), confirming previous research that highlighted the essential role of skilled labor in oil palm farming (Bankole et al. 2018; and Jamhari et al. 2025). Non-linear effects were observed for land area, chemical fertilizer, and labor variables, showing increasing marginal returns. Meanwhile, the squared term of plant age negatively impacted yield, indicating a decline after the optimal growth period.

Interaction effects revealed that fertilizer application synchronized with plant age significantly improved yields (interaction coefficient between plant age and chemical fertilizer: 0.111, $p < 0.10$), reflecting enhanced nutrient uptake during specific growth phases (Dubos et al. 2022). Conversely, a negative interaction between chemical fertilizer and labor (-1.125, $p < 0.01$) indicated that fertilizer effectiveness heavily depended on the availability of skilled labor for proper management. These findings emphasized the importance of balanced input management and human resource capacity development to optimize production efficiency. Overreliance on increasing input quantities without considering supporting factors may lead to resource wastage and long-term efficiency losses (Yanita and Suandi 2021).

Overall, the SMF analysis provided valuable insights into the factors influencing technical efficiency and technology gaps among smallholder oil palm farmers in Riau. Optimizing resource allocation, particularly through coordinated management of labor and inputs, was crucial for bridging technology gaps and enhancing productivity at the meta-frontier level. This study offers theoretical and practical contributions that can guide policy formulation to improve the productivity and sustainability of the smallholder oil palm sector, especially in Riau

Technical efficiency and technology gap by ISPO certification status. This study evaluated the technical efficiency and technology gap ratio of smallholder farmers in Riau, Indonesia, using the Stochastic Meta-Frontier (SMF) method. The three primary indicators were assessed: technical efficiency (TE), technology gap ratio (TGR), and meta-technical efficiency (MTE); the results were presented in Table 4.

Technical efficiency (TE). The SMF estimation showed that smallholder oil palm farmers with ISPO certification exhibited a higher average technical efficiency of 0.932. In contrast, non-ISPO farmers had an average TE of 0.893. This finding provided empirical evidence that ISPO certification positively influenced farmers' capacity to manage production inputs optimally, resulting in TE values approaching unity. Previous studies reinforced this conclusion. Varina et al. (2020b) found that farmers receiving external support (partner farmers) exhibited higher TE (0.713) compared to independent farmers (0.679). Similarly, Yuhendra et al. (2022) reported higher TE values for oil palm farmers integrating cattle farming in Riau Province, achieving 94.49% efficiency compared to 82.40% for non-integrated farmers. Compared to these studies, the TE values found in this research, particularly among ISPO-certified farmers, were notably higher, highlighting the positive impact of certification on technical efficiency.

Table 4. Estimated TE, TGR, and MTE of smallholder farmers by ISPO Certification

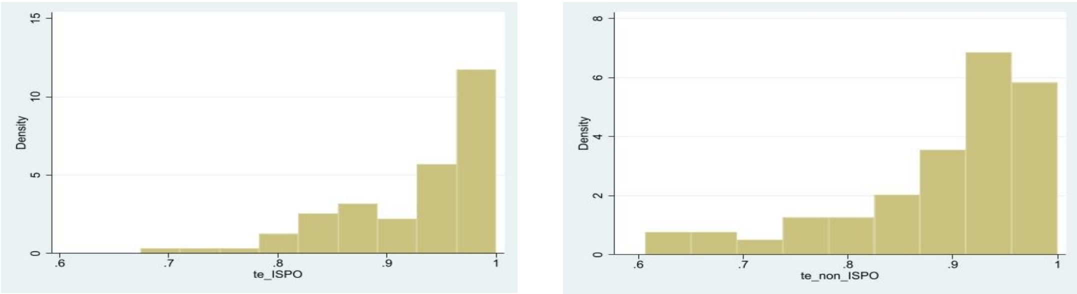
Indicator	Mean	Std. Dev.	Min.	Max.
ISPO certified:				
Technical efficiency (TE)	0.932	0.073	0.674	1
Technology gap ratio (TGR)	0.891	0.104	0.556	1
Meta-technical efficiency (MTE)	0.836	0.149	0.421	1
Non-ISPO certified:				
Technical efficiency (TE)	0.893	0.099	0.606	1
Technology gap ratio (TGR)	0.889	0.105	0.591	1
Meta-technical efficiency (MTE)	0.803	0.167	0.374	1

Source: Own computation using STATA/MP17.0

Figure 2 displayed the distribution of technical efficiency values among smallholder oil palm plantations in Riau according to ISPO certification status. The TE scores of ISPO-certified farmers ranged from 0.674 to 1, indicating greater and more reliable efficiency. In contrast, non-certified farmers displayed a wider TE range, from 0.606 to 1, reflecting greater variability and lower average efficiency. These results suggested that ISPO certification was associated with better technical performance, likely due to improved management practices, enhanced input access, and adoption of advanced technologies. The narrower TE range observed among certified farmers reflected more uniform efficiency, which could be attributed to structured support and compliance with ISPO standards.

Differences in technical efficiency indicated that ISPO-certified smallholder oil palm farmers possessed superior managerial capacity and institutional support, enabling them to operate closer to their potential production frontier. Although absolute production levels, measured in Fresh Fruit

Bunches (FFB), tended to be lower among ISPO farmers, their higher TE values reflected more efficient input utilization. This finding aligns with the production frontier theory proposed by Coelli et al. (2005), which conceptualizes technical efficiency as a relative measure of output maximization given a specific input combination, emphasizing productive efficiency rather than output quantity alone. The study empirically demonstrated that ISPO certification significantly enhanced technical efficiency among smallholder oil palm farmers in Riau Province. Certified farmers demonstrated more effective input management compared to their non-certified counterparts. Therefore, strengthening certification programs and providing continuous technical assistance were essential to improve efficiency further and support sustainable smallholder oil palm production.



a) Technical efficiency for ISPO certified

b) Technical efficiency for non- ISPO

Figure 2. Technical efficiency histogram categorized by ISPO certification status
Source: Own computation using STATA/MP17.0

Technology gap ratio (TGR). The TGR measures the degree of alignment between farmers' technology and the highest technological frontier (meta-frontier). It is calculated as the group's technical efficiency ratio to the meta-frontier efficiency. A TGR value close to one indicated a minimal technology gap and near-optimal technology use. The results showed that ISPO-certified farmers had a slightly higher average TGR (0.891) than non-ISPO farmers (0.889), suggesting that certification contributed to reducing the technology gap by encouraging the adoption of better agricultural technologies. Although the difference was marginal, it supported the notion that ISPO certification facilitated the transition from traditional to improved practices, aligning farmers closer to the best available technology.

These findings aligned with previous studies (e.g., Varina et al. 2020b), highlighting that technology adoption varied by support mechanisms and institutional arrangements. The ongoing technology gap highlighted the necessity for focused policies to improve the dissemination and adoption of technology, aiming to achieve optimal efficiency at the meta-frontier level and foster sustainable competitiveness among smallholder oil palm farmers.

Meta-technical efficiency (MTE). Meta-Technical Efficiency (MTE) comprehensively assessed farmers' ability to optimize input use relative to the meta-frontier, reflecting the highest achievable production technology. ISPO-certified farmers demonstrated a higher average MTE (0.836) than non-ISPO farmers (0.803), indicating superior efficiency not only in managing inputs (TE) but also in operating closer to the best available technology (TGR). This suggested that ISPO certification strengthened both technical and technological capabilities among smallholders.

However, MTE and TGR values below one revealed existing efficiency gaps, attributable to technological access, managerial skills, and institutional support limitations. Therefore, improving MTE required expanding the adoption of appropriate technologies and enhancing farmers' technical capacity through continuous training and extension services. Furthermore, fostering farmer institutions and multi-stakeholder partnerships—including financial institutions, cooperatives, extension agents, and private sector actors—was essential for knowledge transfer and sustainable technology innovation. Such collaboration was vital to bridging the technology gap and promoting long-term efficiency improvements in smallholder oil palm production.

CONCLUSIONS AND RECOMMENDATIONS

This study was the first to investigate technical efficiency differences between ISPO-certified and non-certified smallholder farmers in Riau Province, addressing a notable empirical gap in the literature. Its primary objective was to assess whether ISPO certification enhances resource use efficiency and plantation management among smallholder oil palm farmers. Using the stochastic meta-frontier (SMF) method, this study comprehensively analyzed technical efficiency and technology gaps across various farmer groups. By evaluating technical efficiency (TE) and technology gap ratio (TGR), the research offers robust evidence on the productivity and development potential of smallholder oil palm plantations in Riau, thereby supporting policy formulation for sustainable palm oil development in Indonesia, focusing on Riau.

Among ISPO-certified farmers, oil palm production was influenced significantly by using chemical fertilizers, the age of palm trees, and the interaction between land size, tree age, and organic fertilizer application. In contrast, the production performance of non-ISPO farmers was affected by tree age, labor input, chemical fertilizer use, and their interactions. While socio-economic factors did not significantly impact technical inefficiency, farm management practices played an important role in shaping the performance of non-ISPO farmers.

Meta-frontier analysis revealed higher technical efficiency (TE) among ISPO-certified farmers (0.932) compared to non-certified ones (0.893). However, technology gap ratios (TGR) below one in both groups indicated room for improvement through technology adoption. The higher meta-technical efficiency (MTE) in ISPO farmers reflected better technology implementation. Overall, ISPO certification improved technical efficiency and technology uptake among smallholder oil palm farmers, yet substantial potential remained for further gains through targeted technological assistance and sustainable management practices.

Moving forward, continuous training and adoption of Good Agricultural Practices (GAP) should be prioritized to enhance production efficiency and sustainability, emphasizing critical inputs such as fertilization and the management of palm tree age. Moreover, bridging technology gaps will require expanded access to training programs, advanced technologies, financial support, and the establishment of multi-stakeholder farmer organizations. Offering incentives to farmers who successfully adopt modern technologies could further reduce these gaps. These measures are essential for improving the performance of smallholder farmers within the ISPO certification framework in Indonesia, particularly in Riau Province.

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