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Gender-based technical efficiency analysis of smallholder palm oil plantations in North Sumatra, Indonesia

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Abstract. *Simatupang J, Siregar MA, Sibuea MB. 2025. Gender-based technical efficiency analysis of smallholder palm oil plantations in North Sumatra, Indonesia. Asian J Agric 9: 766-776.* The productivity of smallholder palm oil plantations, managed by both male and female farmers, has recently been low due to inefficient allocation of inputs. Previous efficiency literature in Indonesia has not focused on examining differences in technical efficiency between the two genders of smallholder household heads and has used parametric methods. This study examines which oil palm farming is more efficient based on gender and the determinants of technical efficiency of smallholder farmers in North Sumatra, Indonesia. North Sumatra is a key region for palm oil production in Indonesia, and understanding the efficiency of smallholder farmers in this region can provide valuable insights for the entire industry. Input-output and socio-economic data on palm oil production activities in 2023 were collected from 273 male smallholders and 177 female smallholders. We employed Data Envelopment Analysis (DEA) to assess technical efficiency. We employed the Tobit model to examine the influence of socio-economic factors on the technical efficiency of smallholder farmers in the study area. We found that female smallholders are more efficient than male smallholders. However, inefficient female smallholders must reduce inputs to make their farming efficient. This study highlights the crucial role of access to credit, ICT, and farmer groups in technical efficiency. Government policies are expected to lower interest rates, simplify credit application requirements, develop extensive ICT infrastructure in smallholder plantations, and assist with access to capital and information dissemination within farmer groups. Government intervention is expected to improve the technical efficiency and economic sustainability of smallholder oil palm plantations in North Sumatra.

Keywords: DEA, efficiency, gender, palm oil, smallholder

INTRODUCTION

Oil palm cultivation in North Sumatra, Indonesia, is carried out by three economic actors: state-owned enterprises, private companies, and smallholder oil palm plantations, with the region contributing 10.68% of total national production. Smallholder farmers play a significant role in oil palm production, contributing 34.52% of total output and achieving a productivity level of 3.55 tons per hectare (Direktorat Jenderal Perkebunan 2024). Smallholder oil palm productivity ranks lowest when compared to the other two participants.

Low productivity indicates that smallholder farmers are unable to efficiently produce oil palm, specifically in allocating inputs. Technical efficiency pertains to the ability of agriculture to effectively leverage current technology, aiming to achieve the highest possible output using a given set of inputs, or to minimize input usage while still attaining a designated output level (Minviel and Latruffe 2017). Technical efficiency is influenced by farmer characteristics, such as age, experience, education, and gender of the household head of the family (Mishra et al. 2017; Alem et al. 2018).

Gender encompasses the social roles and identities that individuals adopt, while gender roles serve as the main factors influencing how responsibilities and resources are allocated between men and women (Quisumbing and Doss 2021). Women are acknowledged as an essential asset in the agricultural and rural economies of developing countries (Mishra et al. 2017). When women have access to resources, knowledge, and opportunities in agriculture in developing countries, they are better able to adopt sustainable practices and contribute to increased crop yields, improved food security, increased resilience to climate change, and enhanced biodiversity (Parawansa et al. 2025). However, existing social barriers in agriculture result in underappreciation of women's roles in food production and the rural economy (Quisumbing et al. 2014; Mishra et al. 2017). For instance, women as heads of families, when their husbands migrate out of town or have a widow status, do not have the right to vote to protest when the distribution of palm oil dividends is not transparent, and plasma land ownership is lower than that promised by palm oil companies in Indonesia (Elmhirst et al. 2017; Mawardati et al. 2022).

The issue of social discrimination between men and women as agricultural managers has sparked the interest of agricultural scholars. This study delves into the differences in agricultural efficiency between the two genders, highlighting the need for further investigation. Several previous studies have found that male smallholder oil palm farmers are more efficient than their female counterparts (Koledoye and Deji 2015; Houngue and Nonvide 2020; Obi and Ayodeji 2020; Okorie et al. 2020; Olutumise et al. 2023). The inefficiency of female oil palm farmers is attributed to their limited access to critical resources, such as information, training, and technology. However, other studies have found that female smallholder farmers are more efficient than male ones (Dolisca and Jolly 2008; Effendy et al. 2019). Women outperform their competitors because female farm managers have easier access to new cultivation techniques, credit, and pest management. Furthermore, previous studies found no difference in efficiency between the two genders of household heads, underscoring the need for further research in this area (Missiame et al. 2021; Neupane et al. 2022).

Previous efficiency literature in Indonesia (Alwarritzi et al. 2015; Ariyanto et al. 2020; Abdul et al. 2022; Dalheimer et al. 2022) has not analyzed the differences in technical efficiency between the two genders of smallholder household heads using a non-parametric DEA approach. Many agricultural scholars use non-parametric DEA to address weaknesses in parametric methods, such as overly restrictive assumptions about the relationship between inputs and outputs (Anang et al. 2020). This study focuses on examining the efficiency of oil palm smallholders based on the gender of the household head to add to the existing efficiency literature in Indonesia. This study seeks to assess the technical efficiency of smallholder oil palm farmers, taking into account the gender of the head of the household through Data Envelopment Analysis (DEA), while also investigating the factors that influence technical efficiency using Tobit regression analysis. Achieving high technical efficiency in smallholder oil palm plantations in North Sumatra can support SDG 5 on achieving gender equality and SDG 12 on ensuring sustainable consumption and production patterns.

MATERIALS AND METHODS

Research area and sampling method

North Sumatra Province has the third most significant area of oil palm plantations in Indonesia and the fifth most significant area of smallholder oil palm plantations in Indonesia. In 2023, the area of oil palm plantations in North Sumatra Province consisted of 35.60% smallholder plantations, 21.98% state-owned plantations, and 42.42% private companies (Direktorat Jenderal Perkebunan 2024).

A multi-phase sampling methodology was used to identify smallholder oil palm farmers in North Sumatra. We selected research locations based on the zoning of North Sumatra: the East Coast, Highlands, and West Coast. Asahan District represented the East Coast, Simalungun District represented the Highlands, and Padang Lawas District represented the West Coast. The selected regencies were determined by the highest levels of palm oil production from smallholder plantations in each region. The next stage involved selecting sub-districts based on the most significant palm oil production from smallholder plantations in each district. We selected Bandar Pulau Sub-district for Asahan District, Hatonduhan Sub-district for Simalungun District, and Lubuk Barumun Sub-district for Padang Lawas District. The next stage was the selection of villages based on statistical information on smallholder oil palm plantations in each district. This study selected Gonting Malaha and Padang Pulau Villages for Bandar Pulau Sub-district, Buntu Bayu and Buntu Turunan Villages for Hatonduhan Sub-district, and Aek Lancat and Pagaran Mompang Villages for Lubuk Barumun Sub-district (Figure 1).

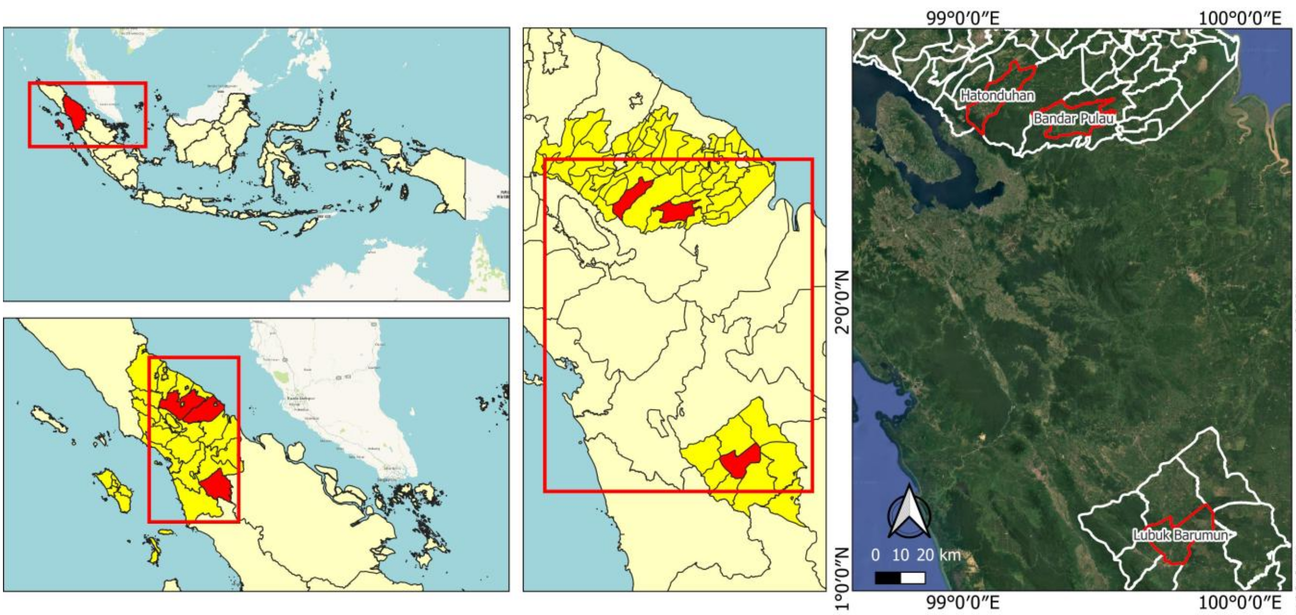

Figure 1. Location of the study

There are 63,840 smallholder oil palm farmers in the three sub-districts. Using the Slovin method with a 5 percent margin of error, the minimum sample size was 398 farmers. Since no data is available on smallholder oil palm farmers in each village, we used simple random sampling to select smallholder farmers as research samples with the same number of samples in each village. Thus, the total sample was 75 smallholder farmers for each village, and the total research sample was 450 smallholder farmers.

This study focuses on comparing the efficiency of oil palm small-scale farmers by gender. The total sample comprised 273 male smallholder farmers and 177 female farmers. The selection of female farmer samples was based on their widowed status because their husbands had died or because they were divorced. The distribution of smallholder farmers' samples based on the gender of the head of the family is presented in Table 1.

DEA model

Koopmans (1951) characterized technical efficiency for a producer as the situation in which enhancing output necessitates either a reduction in at least one additional output or an augmentation in at least one of the inputs. On the other hand, a decrease in input requires a corresponding reduction in at least one additional input or a decrease in at least one output. Efficiency assessments yield two critical insights: guidance for optimal resource allocation and strategies to minimise unnecessary inputs (Anang et al. 2020). Scholars employ a variety of methodologies to assess the technical efficiency of smallholders, which can generally be classified into two main categories: parametric and non-parametric methods (Wang and Hu 2021). The data envelopment analysis model was chosen for this research because it does not require prior assumptions about the relationship between inputs and outputs, operates independently of a model that identifies sources of inefficiency, and effectively handles multiple outputs (Anang et al. 2020).

The DEA model is divided into two categories: input-oriented and output-oriented models, depending on the orientation employed. The input-oriented DEA model emphasizes the minimization of inputs while maintaining a specified level of output. The output-oriented DEA model emphasizes the goal of maximizing the proportional enhancement in output generated from a specified set of inputs (Coelli et al. 2005). The input-oriented DEA model is more appropriate for this study because smallholder oil palm farmers can only control inputs. In other words, they cannot increase output due to technological limitations and land suitability (Toma et al. 2015). The DEA model is classified into two distinct types according to specific assumptions: CCR-DEA is based on the premise of constant returns to scale, while BCC-DEA is grounded in the concept of variable returns to scale (Nguyen et al. 2020). The DEA CRS model is applicable when a consistent relationship exists at scale between the output and input of the analyzed decision-making unit. The DEA VRS model is suitable for decision-making units that cannot be uniformly assessed alongside all units within a particular sector (Piran et al. 2020). The separation of technical efficiency and scale efficiency to capture the actual managerial expertise of smallholder farmers is the reason we used the VRS assumption DEA model (Perrigot and Barros 2008).

In this context, θ_k represents the Technical Efficiency (TE) value for the kth smallholder plantation, which varies between 0 and 1. The variable y_j denotes the vector of fresh fruit bunch outputs from oil palm, while x_i indicates the vector of input quantities, including land, fertilizer, pesticide, and labor. Additionally, λ refers to the weighting vector.– The VRS constraint is expressed as $\sum_{k=1}^{m} \lambda_k = 1$. As a result, the formulation for DEA input orientation, along with the assumptions of VRS for evaluating the technical efficiency of oil palm smallholder plantations, can be articulated as follows (Piran et al. 2020):

$$min\theta_k \quad [1]$$

Subject to

$$-y_j + y_{jk}\lambda_{jk} \geq 0;\ \forall_j = 1$$

$$\theta_k x_i - x_{ik}\lambda_k \geq 0;\ \forall_i = 1, \ldots, 4$$

$$\sum_{k=1}^{m} \lambda_k = 1;\ \forall_k = 1, \ldots, m$$

$$\lambda \geq 0$$

Where:

θ_k : Technical Efficiency (TE) value for the kth smallholder plantation

y_j : Fresh fruit bunch (kg FFB)

x_1 : Land (ha)

x_2 : Labor (man–days)

x_3 : Fertilizer (kg)

x_4 : Pesticide (litre)

$\forall_k$: Number of samples, where the sample of male farmers is 1,..., 273 and female farmers is 1,..., 177, and the pooled sample is 1,..., 450

Table 1. Sample distribution by gender and research location

Regions/District	Sub-district	Village	Sample size Male	Female	Total
East Coast/Asahan	Bandar Pulau	Gonting Malaha	47	28	75
		Padang Pulau	47	28	75
Highlands/Simalungun	Hatonduhan	Buntu Bayu	47	28	75
		Buntu Turunan	46	29	75
West Coast/Padang Lawas	Lubuk Barumun	Aek Lancat	40	35	75
		Pagaran Mompang	46	29	75
Total			273	177	450

Source: Pre survey data

The assessment of Equation (1) relates to the technical efficiency of the jth small farmers' oil palm, in comparison to all other smallholder plantations within the sample set. We also measure the return to scale of each smallholder oil palm plantation in the sample through scale yield performance (λ). When the sum of the calculated weights (λ) of the reference DMUs (benchmark) surpasses one, there will be an increase in returns to scale. If it is below one, the scale returns will decrease. In the context of CRS, the computed weighted sum (λ) for the reference (benchmark) DMU is precisely one (Piran et al. 2020). This study assumes that there are similarities in the use of oil palm cultivation technology in the three regional zones in North Sumatra. Additionally, we examine the technical efficiency of oil palm small farmers by analyzing the gender of the family head through an independent sample test. This study uses MaxDea 12 software to examine technical efficiency with the input-oriented VRS assumption DEA model.

Tobit analysis

This investigation, after to the efficiency calculation via DEA, aims to uncover the elements influencing the efficiency of small farmers' oil palm. The analysis will concentrate on agricultural factors linked to technology and socio-economic traits, such as the gender of the household head. In empirical studies focused on efficiency, the efficiency value ranges from 0 to 1, which restricts the observation of independent variables to a limited extent. Standard regression models, like the Ordinary Least Squares (OLS) model, prove inadequate for these analyses due to the left and right censoring of the dependent variable, which leads to inconsistent parameter estimates (Cecchini et al. 2021). The Tobit model adeptly tackles this issue, and many academics employ this model for empirical studies on efficiency factors. The Tobit model, often referred to as the restricted dependent variable model, employs maximum likelihood estimation to perform regression analysis on the dependent variable, aiming to identify the factors influencing the efficiency of smallholder oil palm farmers (Zhou et al. 2022).

In this context, θ_k represents a hidden dependent variable that is measured within the range of 0 to 1, specifically indicating the efficiency score of oil palm smallholder plantations, while being censored outside this interval. The term α represents the unknown intercept, and ε_k follows an independent and identically distributed normal distribution with a mean of 0 and a variance σ^2. The vector Z_n encompasses the covariates, while β signifies a vector of parameters that require estimation, aimed at quantifying the linear influence of socio-economic explanatory variables on the efficiency score of oil palm smallholder plantations.– The entire sample is analyzed using Equations (2) and (3). Consequently, the assessment of elements influencing the technical efficiency of male smallholder farmers (θ_{km}) and the elements affecting the technical efficiency of female smallholder plantations (θ_{kf}) can be articulated in the following manner:

$$\theta_{km} = \alpha + Z_n\beta + \varepsilon_m;\ \forall_n = 1,2,\ldots,12 \quad [2]$$

$$\theta_{kf} = \alpha + Z_n\beta + \varepsilon_f;\ \forall_n = 1,2,\ldots,12 \quad [3]$$

Where:
θ_{km} : Technical efficiency of male smallholder farmers
θ_{kf} : Technical efficiency of female smallholder farmers
β : Socio-economic parameters
Z_1 : Age
Z_2 : Education
Z_3 : Farming experience
Z_4 : Household size
Z_5 : Seedling category
Z_6 : Trees
Z_7 : Credit
Z_8 : Distance to market
Z_9 : Organic fertilizer
Z_{10} : Farmer groups
Z_{11} : ICT
Z_{12} : Genders

The censored variable θ_j, which reflects the efficiency score of oil palm smallholder plantations derived from equation (4), can be articulated as follows.

$$\theta_k = \begin{cases} \theta_k \ if\ 0 < \theta_k < 1 \\ 1\ if\ \theta_k \geq 1 \\ 0\ if\ \theta_k \leq 0 \end{cases} \quad [4]$$

Before performing the estimation, a correlation analysis is carried out between the DEA input/output and regressors to reduce bias in the Tobit estimation (Coelli et al. 2005). Multicollinearity tests are performed on independent variables through the use of VIF to improve model specifications, and the VIF score is recommended to be below 5 to avoid multicollinearity problems (Marcoulides and Raykov 2019). We use the Breusch Pagan/Cook Weisberg test to assess heteroscedasticity in the model, and p value above alpha indicates no heteroscedasticity (Aguade et al. 2022). Given that the Tobit parameters lack direct interpretability, marginal effects are employed for conducting post-estimation tests on the Tobit regression. Marginal effects tests are conducted to assess the impact on the observed mean value of θ_j in relation to variations in Z_k (Wooldridge 2019). We used STATA 17 software to investigate the Tobit model before and after the estimation.

Data and variables

This study uses primary data collected from smallholder oil palm farmers during production activities in 2023. Data were collected from February to May 2024 through questionnaire interviews with farmers at the designated study locations. The data collected included socio-economic attributes of smallholder oil palm farmers, as well as oil palm inputs and outputs.

Palm oil production (Y) was calculated based on last year's kilograms of fresh fruit bunches. Land (X1) is calculated based on the area of the oil palm plantation in hectares. Labor (X2) is calculated based on the involvement of male and female laborers, both family and wage workers. Fertilizer (X3) includes several chemical fertilizers: urea, NPK, KCL, SP36, ZA, dolomite, and organic fertilizers in kilograms. Pesticides (X4) include several chemical pesticides: Roundup, Gramoxone, and

Paratop, measured in liters. Input and output variables are used to measure technical efficiency.

The age measurement (Z_1) is established based on the number of years of the household head. The evaluation of education (Z_2) is characterized by the cumulative years of formal educational attainment of the family head. Farming experience (Z3) is obtained from the duration of smallholder farmers' involvement in oil palm cultivation. The measurement of household size (Z_4) is determined by the count of individuals residing in the same dwelling. The seed category (Z_5) is defined as a dummy variable, based on the classification of certified and uncertified seeds. We assign a label of 1 when a farmer uses seeds produced by a government-licensed institution, while uncertified seeds are assigned a label of 0. Trees (Z_6) are measured based on the number of productive plants (3-25 years) per plot managed by smallholder farmers. Credit (Z_7) as a dummy variable is determined based on small farmers who take loans from banks or other formal financial institutions being labeled 1, and not taking loans being labeled 0. Distance to market (Z_8) is measured in kilometers based on the distance from home to the input market. Organic fertilizer (Z_9) is measured based on the experience of smallholders farming using organic fertilizer for years. Farmer groups (Z_{10}) are measured based on the smallholders' experience joining farmer groups over the years. ICT (Z_{11}) is measured based on the experience of smallholder farmers using electronic gadgets to obtain information and communication on oil palm farming management in units of years. Gender (Z_{12}) is a dummy variable, where male heads of household are labeled 1, while female heads of household are labeled 0. Table 2 shows a descriptive analysis of smallholder oil palm plantations.

RESULTS AND DISCUSSION

Characteristics of samples

The characteristics of the sample are presented in Table 3. In terms of input variables, the land owned by male smallholders is 26.58% larger compared to that of female smallholders. The labor and pesticides used by male smallholders are 15.75% and 25.88% more than those used by female smallholders. The three inputs differ significantly between the two groups of smallholder samples. Only the amount of fertilizer used by both groups of smallholder samples is considered the same. Regarding output variables, male smallholders' oil palm production is 21.58% greater than that of female smallholders.

Regarding socio-economic variables, the age of male smallholders is 4.29% younger than that of female smallholders. Male smallholders' number of oil palm plants is 26.48% greater than that of their competitors. Female smallholders have more experience in oil palm farming and use organic fertilizers by 18.29% and 141%, respectively, than male smallholders. The majority of female smallholders use more certified seeds than male smallholders. However, only 25% of female smallholders access credit, while 51% of male smallholders access credit. Female smallholders' land is 20.92% closer to the input market than their competitors. Finally, female smallholders have been members of farmer groups longer and use ICT by 74.92% and 18.02%, respectively, than their competitors.

Table 2. Descriptive analysis of smallholder oil palm plantations in North Sumatra, Indonesia

Variables	Mean	Std.dev	Min	Max
Input-Output				
Land (ha)	2.57	1.38	0.52	7
Labor (man–days)	97.61	48.85	16	244
Fertilizer (kg)	697.19	591.34	60	3640
Pesticide (litre)	12.47	6.72	2.5	34
Palm Oil (kg FFB)	54562.22	28440.46	11600	148800
Socio-economic				
Age (years)	51.78	5.33	36	64
Education (years)	12.42	1.96	9	17
Farming experience (years)	20.06	4.39	12	35
Household size (numbers)	5.54	0.84	4	7
Seedling category (0: uncertified; 1: certified)	0.59	0.49	0	1
Trees (numbers)	337.49	184.66	65	990
Credit (1: get access to credit; 0: otherwise)	0.41	0.49	0	1
Distance to market (km)	2.59	0.66	1.4	4.2
Organic fertilizer (years)	2.00	3.05	0	10
Farmer groups (years)	6.26	5.92	0	16
Information and communication technology/ ICT (years)	5.11	1.73	0	8
Genders (0: female; 1: male)	0.61	0.49	0	1

Source: Primary Data Analysis

Efficiency of smallholder oil palm plantations

The findings of our study indicate that the average technical efficiency for both female and male smallholders was 0.882, as shown in Table 4. Based on the VRS assumption, female and male smallholders need to reduce input usage by 10.8% and 12.75%, respectively, to make their oil palm farming efficient. Additionally, our findings indicate that female smallholders demonstrated a higher level of efficiency compared to their male counterparts. The efficiency score of female smallholders was 1.95% higher than that of their competitors. This value means that all smallholder oil palm farmers need to reduce input usage by 11.8% to make their oil palm farming efficient.

Figure 2 reveals that female samples are more efficient than male samples. The number of technically efficient female farmer samples is 18.64% and the number of efficient male farmer samples is 12.45%.

Table 3. Sample characteristics based on the gender of smallholder oil palm

Variables	Male (N=273)		Female (N=177)		Prob T
	Mean	Std.dev	Mean	Std.dev	
Input-Output					
Land (ha)	2.81	1.42	2.22	1.24	0.000
Labor (man-days)	103.12	49.28	89.09	47.05	0.003
Fertilizer (kg)	698.88	613.18	694.59	557.67	0.939
Pesticide (litre)	13.57	6.93	10.78	6.01	0.000
Palm Oil (kg FFB)	58657.88	29044.84	48245.20	26336.50	0.000
Socio-economic					
Age (years)	50.88	5.19	53.16	5.25	0.000
Education (years)	12.43	1.91	12.39	2.03	0.825
Farming experience (years)	18.72	3.59	22.14	4.70	0.000
Household size (numbers)	5.50	0.92	5.59	0.72	0.262
Seedling category (0: uncertified; 1: certified)	0.43	0.50	0.84	0.37	0.000
Trees (numbers)	367.78	191.20	290.77	163.93	0.000
Credit (1: get access to credit; 0: otherwise)	0.51	0.50	0.25	0.44	0.000
Distance to input market (km)	2.82	0.62	2.23	0.55	0.000
Organic fertilizer (years)	1.29	2.47	3.11	3.50	0.000
Farmer groups (years)	4.84	5.82	8.46	5.40	0.000
ICT (years)	4.77	1.61	5.63	1.79	0.000

Source: Primary Data Analysis

Table 4. Efficiency scores by gender and pooled sample

Efficiency	Male (N=273)		Female (N=177)			Pooled (N=450)	
	Mean	Std.dev	Mean	Std.dev	Prob T	Mean	Std.dev
PTE	0.875	0.088	0.892	0.087	0.045	0.882	0.088
Input reduction (%)	12.75		10.8			11.8	

Source: Primary data analysis

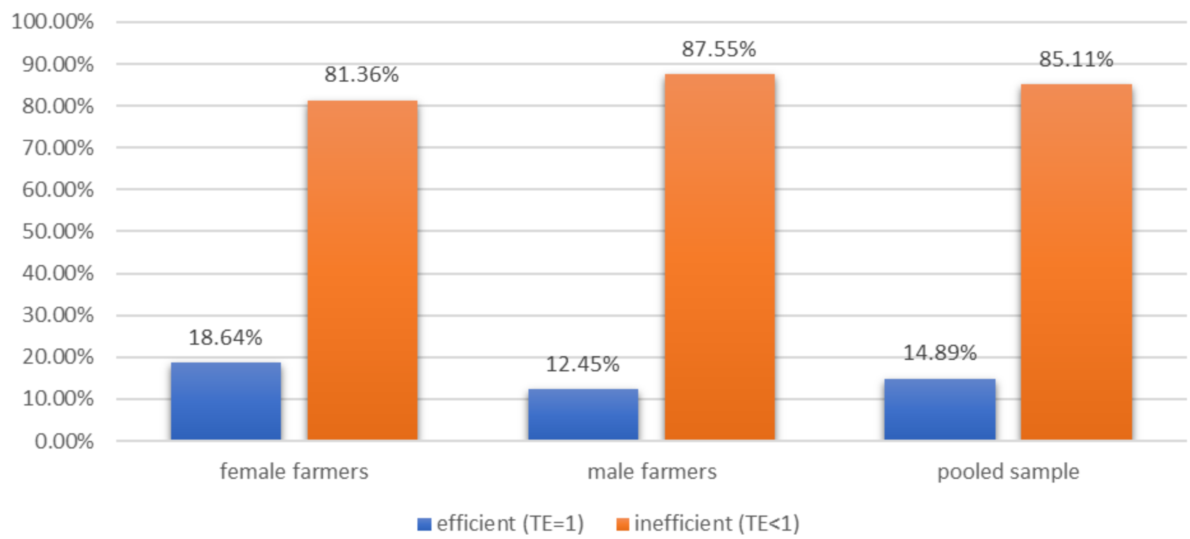

Figure 2. Share of efficient and inefficient smallholder oil palm farmers. Source: Primary data analysis

Determinant of technical efficiency

This study examines the elements influencing the productivity of smallholder oil palm plantations, operating under the premise of variable returns to scale. Before undertaking a more detailed characterization of the Tobit model estimation, it is crucial to examine a concise overview of the post-estimation test results to evaluate possible model specifications. The VIF test indicated that multicollinearity was not present among the independent variables. Based on the model specification test in Table 5, the test produced mean values for the factor model estimates assessing the efficiency of female, male, and pooled smallholder farmers of 1.65, 2.09, and 1.82, respectively, with no variable exceeding a VIF of 5. We found that the Breusch Pagan/Cook Weisberg p-value for the three sample groups was above the alpha level, indicatimg no evidence of heteroscedasticity. The likelihood ratio test results of 253.7, 446.75, and 659.73 for the models assessing the factors influencing the efficiency of female, male, and pooled smallholder farmers, respectively, along with a p-value of 0.000 in all instances, indicate that our overall model is statistically significant when juxtaposed with the null hypothesis, which posits that all predictor coefficients are zero. The coefficient of Marginal Effect (ME) is utilized in the factor model that assesses efficiency, as it signifies the change in magnitude between the dependent and independent variables (Simatupang and Nababan 2023).

The age of the head of the household, educational background, and the number of trees show a positive and significant influence on the efficiency scores of male small farmers, as well as the overall sample. The ME coefficient values for the variables related to the age of the head of the household, level of education, and plants in the factor model evaluating the efficiency of male farmers are 0.0016, 0.0023, and 0.00003, respectively. The ME coefficient value of 0.0023 suggests that an extra year of formal education for male small farmers leads to a 0.0023% enhancement in their technical efficiency. Related to the distance to the market, the negative and significant impact on the efficiency scores of male small farmers and the pooled sample. The ME coefficient value of -0.0287 indicates that an increase of one kilometer in distance from the house to the input market results in a decrease of 0.0287% in the technical efficiency of male small farmers.

This study revealed significant adverse effects of farming experience, family size, and seed category on the efficiency scores of female smallholders, male smallholders, and the combined sample of smallholder farmers. However, the substantial impact of farmer groups and ICT on the efficiency scores of female smallholders, male smallholders, and the overall sample of smallholder farmers offers hope for potential improvement. The ME coefficient of farmer groups is 0.0048 in the sample model of male and female farmers, indicating that one year of experience in farmer groups has the potential to increase their technical efficiency by 0.0048%. The ME coefficient of ICT in the three sample groups is 0.0245, 0.0236, and 0.0263, respectively. These values mean that one year of farmer experience using ICT has the potential to increase their technical efficiency by 0.0245%, 0.0236%, and 0.0263%. Notably, credit was found to have substantial effects on the efficiency score of female smallholder farmers. Lastly, the study found no significant effect of organic fertilizer on the three efficiency models examined.

Discussion

The technical efficiency of female smallholders is higher than that of male smallholders. The statement can be proven that one hectare of land by female smallholders can produce 21.98 tons of palm oil, while the productivity of male smallholders' land is only 21.09 tons per hectare. When comparing the test on productivity for both samples, we found that female smallholders' land productivity is significantly higher than that of male smallholders. According to Koopmans (1951), technical efficiency occurs because of high productivity, which comes from the ability to manage minimum input to produce output.

Table 5. Determinants of technical efficiency

Variables	Male (N=273)		Female (N=177)		Pooled Sample	
	ME	P>|z|	ME	P>|z|	ME	P>|z|
Age (years)	0.0016	0.011*	0.0009	0.282	0.0018	0.001*
Education (years)	0.0023	0.049*	0.0006	0.666	0.0168	0.084*
Farming experience (years)	-0.0025	0.008*	-0.0030	0.002*	-0.0042	0.000*
Household size (numbers)	-0.0055	0.053*	-0.0094	0.030*	-0.0035	0.152
Seedling category (0: uncertified; 1: certified)	-0.0952	0.062*	-0.0289	0.001*	-0.0183	0.000*
Trees (numbers)	0.00003	0.036*	0.0000	0.511	0.0000	0.035*
Credit (1: get access to credit; 0: otherwise)	-0.0038	0.432	-0.0120	0.080*	-0.0048	0.241
Distance to market (km)	-0.0287	0.000*	-0.0107	0.119	-0.0177	0.000*
Organic fertilizer (years)	0.0012	0.233	0.0011	0.276	0.0003	0.719
Farmer groups (years)	0.0048	0.000*	0.0048	0.000*	0.0044	0.000*
ICT (years)	0.0245	0.000*	0.0236	0.000*	0.0263	0.000*
Gender					-0.0012	0.753
Likelihood ratio	446.75	0.000*	253.7	0.000*	659.73	0.000*
VIF	2.09		1.65		1.82	
Breusch Pagan/Cook Weisberg	0.5663		0.1438		0.1572	

Source: Primary data analysis, *: Indicate significant levels at 90%

Based on in-depth field interviews, female smallholder farmers do not experience discrimination in accessing productive resources, such as land, fertilizer, labor, and oil palm cultivation training. Cover crops and cattle farming, which enhance land conservation, are frequently recommended during training sessions to ensure sustainable smallholder oil palm plantations. Local governments and farmer groups provide training. Female smallholder farmers focus on leveraging the knowledge gained from the training to increase oil palm productivity and meet their household needs. In contrast to male smallholders, they have businesses other than oil palm as additional sources of household income. The large amount of time spent on businesses other than oil palm causes male smallholders to be less focused on managing their farms.– Thus, female smallholders are more efficient than male smallholders because they are more productive in using inputs than men. Our findings align with previous studies (Missiame et al. 2021; Obokare et al. 2024). Our analysis revealed that gender did not have a significant impact on the technical efficiency of smallholders within the pooled sample. This finding indicates that the gender of smallholders does not play a significant role in enhancing efficiency.

Socio-economic variables influence technical efficiency improvements across all three sample groups. Farmer age has the potential to enhance the technical efficiency of male smallholders, as well as in the combined samples. This situation illustrates that the technical efficiency of smallholder oil palm plantations managed by older male farmers and the combined sample is significantly greater than that of smallholder oil palm plantations managed by younger farmers. This result is possible because older smallholders have better abilities, skills, and experience in agricultural activities, which can trigger increased technical efficiency. Our findings align with those of Anang et al. (2016) and Tenaye (2020). Conversely, Baiyegunhi (2020) and Simatupang and Nababan (2023) and Ojo found that older smallholders are more efficient than younger ones, while Simatupang et al. (2025) found that the age of the household head did not significantly affect smallholder efficiency.

The results demonstrate that a higher educational attainment of the head of the household is correlated with improved technical efficiency. That finding means that small male farmers and pooled samples with high formal education tend to adopt and utilize oil palm management technology. This result is consistent with the results reported by Alwarritzi et al. (2015) and Abdul et al. (2022).

Our study highlights that smallholder farmers in all three sample groups with less experience are more efficient than those with more experience. This is probably because smallholder farmers with less experience (<18 years) possess extensive knowledge about oil palm and are more proactive in seeking new information to improve oil palm productivity and efficiency.

Large household sizes can potentially reduce the technical efficiency of smallholder farmers in the three sample groups. This finding indicates that smallholder farmers with large household sizes are directly linked to increasing household expenditures and face challenges in accumulating capital to purchase oil palm inputs. A relatively significant decrease in input costs impacts the production and technical efficiency of smallholder oil palm farmers. This finding is in line with the findings of Ramezani et al. (2022). However, Mengui et al. (2019) revealed a positive relationship between household size and the technical efficiency of smallholder farmers.

Certified oil palm seeds are provided by companies holding certified seed licenses, while uncertified oil palm seeds are offered by unlicensed companies or individuals to smallholder farmers. The research findings indicate that uncertified seeds have the potential to improve the technical efficiency of smallholder farmers across three sample groups. This is possible because the seeds used by farmers are of good quality, even though they are not sourced from official (certified) institutions. They are likely better suited to the local conditions in the study area, including land and climate suitability. On the other hand, certified (high-quality) seeds require intensive management that may not be feasible for smallholder farmers. Farmers using uncertified seeds have a higher ability to minimize input use to achieve technically efficient input use levels than farmers using certified seeds. These results align with the conclusions drawn by Setiawan et al. (2023). However, research conducted by Abdul et al. (2022) indicates that certified seeds have a positive effect on the technical efficiency of oil palm plantations due to suitable climatic conditions.

We found that the more productive trees planted per hectare, the higher the efficiency of male smallholders and pooled samples. A density of 110-160 trees per hectare can effectively balance between the immediate canopy's closure during the young phase, the abundance of palm trees (i.e., bunches) in the developing adult phase, and the minimized competition for light among palm trees in the adult phase (Woittiez et al. 2017). If the average number of productive trees planted by male smallholders and pooled samples is 136 trees per hectare and 134 trees per hectare, respectively, then around 15% and 16.25% of productive trees can still be added by smallholders to increase their efficiency. Productive trees (high-yielding phase) range from 8 to 14 years after planting (Woittiez et al. 2017). This finding is consistent with the conclusions reached by Abdul et al. (2022).

We found that credit access is negatively related to the technical efficiency of female smallholder farmers. The findings indicate that female smallholder farmers lacking access to credit from formal financial institutions demonstrated greater efficiency compared to their counterparts who did access such credit. In-depth interviews with female smallholder farmers revealed that participants obtained funding from informal sources, including friends, relatives, input providers, and collectors. The sources offered reduced interest rates and processing fees, while requiring minimal collateral. The accessibility of informal sources facilitated their acquisition of input technology, which has the potential to enhance productivity and technical efficiency in oil palm farming. Tenaye (2020) highlights that smallholder farmers encounter numerous challenges in obtaining credit, such as difficulties with timing and quantity of credit, guarantee demands, and terms of repayment. Haryanto et al. (2023) demonstrated that simplifying collateral requirements and reducing interest rates on loans from formal sources may enhance farmers' access to credit from formal financial institutions, thereby boosting agricultural efficiency and productivity.

This study found that the closer the distance to the input market, the higher the efficiency score of male smallholder farmers and pooled samples. The closer the distance from home to the market, the lower the transportation costs for purchasing inputs. Smallholder farmers can divert low transportation costs to purchase other input technologies, which aim to increase the production and efficiency of oil palm smallholder plantations. This finding is in line with the findings of Teferra et al. (2018).

Our findings indicate that smallholders with prolonged membership in farmer groups possess the capacity to enhance the technical efficiency of smallholders across all three sample groups. This finding means that smallholders who are members of farmer groups have the opportunity to increase their knowledge through information exchange and cooperation (such as making water channels), which they actively engage in, thereby increasing production and efficiency. This finding aligns with previous studies (Bairagi and Mottaleb 2021; Olagunju et al. 2021), which found that smallholder farmers in farmer groups have access to agricultural information, credit, and inputs, which in turn improves their technical efficiency.

This study found that seasoned farmers leveraging ICT can enhance the technical efficiency of smallholder farmers across all three sample groups. This finding indicates that smallholder farmers who actively seek new information and communicate with farmer groups, academics, and the government through electronic devices can more easily increase their knowledge and improve the technical efficiency of oil palm smallholder farming. The results align with earlier research (Mwalupaso et al. 2019; Kang et al. 2023), indicating that smallholder farmers consistently engaged in the use of ICT, as well as mobile phones, can enhance their technical efficiency. This study can be summarized in the conceptual diagram in Figure 3.

In conclusion, this study contributes to the literature on oil palm smallholders in North Sumatra by analyzing differences in technical efficiency across gender groups and identifying determinants affecting efficiency among male, female, and pooled farmers. The results show that female smallholders are more technically efficient because they use inputs more effectively to achieve high productivity, despite being older, having larger households, and generally having lower education levels. Strengthening government policy support is essential to enhance the efficiency of female smallholders. Interventions such as lower interest rates, easier access to credit (KUR), support for replanting programs, ICT infrastructure in rural areas, and farmer-group training can improve capital access and input use, thereby increasing productivity, efficiency, and household income. In the long term, these policies can promote economic sustainability and support biodiversity in small-scale plantations. Limitations include the omission of input prices and farmer welfare; future studies should integrate these variables and environmental efficiency.

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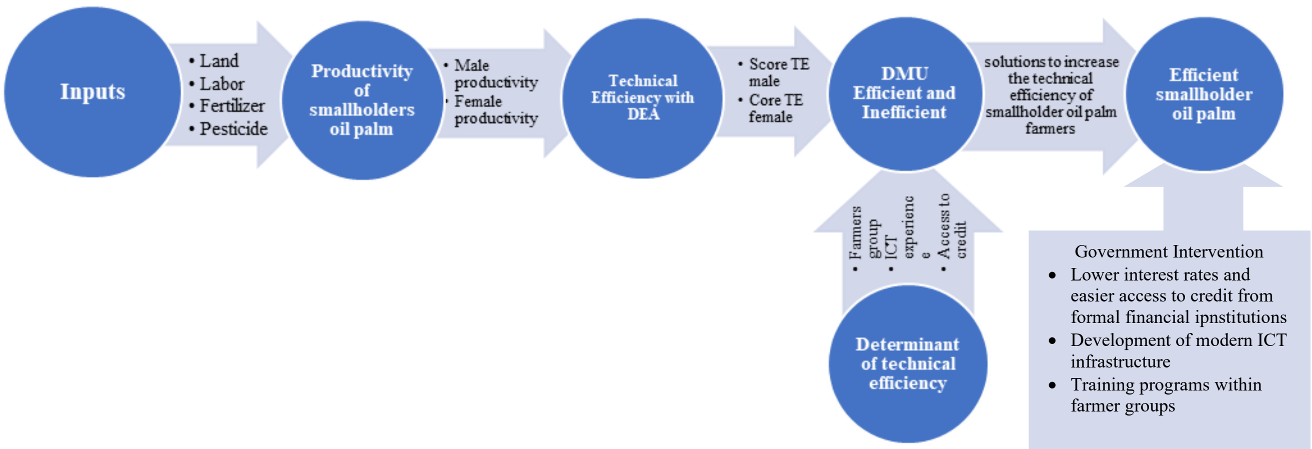

Figure 3. Conceptual diagram for improving the technical efficiency of smallholders oil palm in North Sumatra, Indonesia

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