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Estimating Technical Efficiency of Rice Farming in Indonesia in Pre-crisis Period to Support Sustainable Development: Evaluating Fertilizer Subsidies and Informal Labor

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ABSTRACT

Background: Rice is one of the most essential commodities for maintaining food security in Indonesia. However, the productivity of lowland rice is generally constrained by the inefficient use of inputs; this situation was particularly prevalent in the pre-global crisis years of 2018-2021, influenced by outbreaks of COVID-19 and geopolitical tensions. This study aims to analyze the technical efficiency of lowland rice production in Indonesia and determine the contribution of subsidies for ZA, NPK, granule organic fertilizer and the dominance of informal labor to productivity.

Methods: This study employs the Stochastic Frontier Analysis (SFA) approach, utilizing a Cobb-Douglas-type production function with a multiplicative model and draws on secondary data obtained from the Central Statistics Agency and the Directorate General of Agricultural Infrastructure and Facilities.

Result: The results suggest that all input variables have positive and significant effects on rice production, with granulated organic fertilizers and informal labor showing the highest coefficients. The national average technical efficiency varies over time but progressively improves under the model. Farmers with large-scale businesses have better technical efficiency than those with small-scale ones. Moreover, there's an efficiency gap between various regions. Bali, DKI Jakarta and Gorontalo have the highest efficiency, while West Kalimantan and Central Kalimantan have the lowest efficiency.

Key words: Fertilizer subsidy, Informal labor, Rice farming, SFA, Technical efficiency.

INTRODUCTION

Rice plays an important role as the main staple food for most Indonesian people; it is crucial in food security, making its production a national priority (Handani *et al*., 2021; Antara *et al*., 2023). Efforts to achieve rice self-sufficiency are not just an agricultural goal, but an economic development agenda that impacts various levels of government, from provincial to district governments (Handani *et al*., 2021). It is critical to Indonesia's economic stability and social welfare to meet the population's demand for rice. The inefficient use of production factors in lowland rice farming poses a significant challenge because it has a direct impact on agricultural productivity (Azwar *et al*., 2019; Effendy *et al*., 2023).

Indonesia faces an ongoing challenge of meeting increasing domestic food demand because of population growth and the increasing purchasing power of its citizens (Ruslan, 2021). To effectively address this challenge and ensure national food security, national production capacity must increase. This can be achieved by strategically expanding agricultural land and implementing productivity-enhancing measures (Ruslan, 2021; Hakim *et al*., 2021; Effendy *et al*., 2022). To maintain productivity, the government has long provided subsidies for fertilizers such as ZA, NPK and granular organic fertilizers. This intervention reduces farmers' input costs and boosts production output. However, reliance on subsidies does not guarantee technical efficiency in cultivation practices, especially when it is not accompanied by reforms to the agricultural labor structure, which remains dominated by informal workers.

The period from 2018 to 2021 was crucial in Indonesia's agricultural system and can be considered the pre-global food crisis era. During this period, the COVID-19 pandemic began to impact input distribution, logistics and food price fluctuations. In addition, immediately after this period, global pressures increased due to the Russia-Ukraine conflict and the El Niño phenomenon, disrupting international

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food and fertilizer supplies in 2022-2023 (FAO, 2023; World Bank, 2023).

Improving the technical efficiency of rice farming is critical for Indonesia to achieve food security, especially in major agricultural hubs across the Indonesian archipelago (Hakim *et al*., 2021; Muhardi and Effendy, 2021). By improving the efficiency of resource use in rice production, Indonesia can increase its agricultural output and ensure a stable supply of this essential food commodity for its population.

Technical efficiency in rice farming refers to the ability of farmers to maximize their rice yields from a given set of inputs, including essential resources such as land, labor and fertilizer (Hakim *et al*., 2020; Muhardi and Effendy, 2021). This concept measures how effectively farmers can convert these inputs into rice yields. Previous studies have discussed many aspects of efficiency (Hakim *et al*., 2020; Geffersa and Agbola, 2025; Amare *et al*., 2025; Ruzhani and Mushunje, 2025; Hailu *et al*., 2025), but have not explicitly linked it to the informal labor structure and input subsidies in a Stochastic Frontier Analysis (SFA) model applicable to policy.

Although various studies have highlighted the importance of input subsidies and the role of labor in increasing rice farming productivity, there remains a knowledge gap regarding how fertilizer subsidies-particularly ZA, NPK and granular organic fertilizers-and the dominance of informal labor simultaneously contribute to the achievement of technical efficiency in rice farming in Indonesia. Therefore, this study is guided by the following main questions: (1) To what extent do production inputs such as land, subsidized fertilizer and informal labor affect rice farming productivity? (2) How did the level of technical efficiency of rice farming vary across regions in Indonesia during the pre-global crisis period of 2018-2021? and (3) do larger-scale businesses tend to achieve higher technical efficiency than small-scale businesses? This study aims to fill the gap in the literature regarding the simultaneous relationship between the effectiveness of ZA, NPK, granular organic fertilizer subsidies and the dominance of informal labor on the technical efficiency of lowland rice.

MATERIALS AND METHODS

Data sources and research variables

The data set of ZA, NPK and granular organic fertilizer subsidies was collected from the Directorate General of Agricultural Infrastructure and Facilities database (2022). This was supplemented with data regarding output, rice harvest area and Informal Labor in the Agricultural Sector from the Central Statistics Agency database (CSA, 2025a; CSA, 2025b). The analysis considers data from 2018 to 2021.

The following variables were used in the analysis: output, harvested area, subsidized ZA fertilizer, subsidized NPK fertilizer, subsidized organic fertilizer and informal agricultural labor. The output variable is expressed in terms of rice production, measured in tons of dry milled grain. The harvested area variable is measured in hectares; subsidized ZA fertilizer, subsidized NPK fertilizer and subsidized organic fertilizer are measured in tons; the informal agricultural labor variable is expressed as a percentage. Table 1 shows the descriptive characteristics of the dataset.

Stochastic frontier analysis approach

This study uses the Stochastic Frontier Analysis (SFA) approach to measure the technical efficiency of rice farming in Indonesia. SFA is an econometric method that considers technical inefficiency separate from random errors in the production function. This approach was developed by Aigner *et al*. (1977) and Meeusen and van den Broeck (1977), who both introduced a stochastic frontier model based on production functions.

The stochastic frontier production function model can be stated as follows:

$$Y_i = f(X_i; \beta).\ \exp(\varepsilon_i) \quad ...(1)$$

Where,

Y_i= The output of the i^{th} unit.

X_i= The input vector.

β= The estimated parameter.

$\varepsilon_i = V_i - U_i$.

V_i= Random error component that is normally distributed $N(0,\sigma_v^2)$ and represents random disturbances, such as abnormal weather or measurement errors.

U_i= A non-negative technical inefficiency component that is usually semi-normal, exponential, or normally truncated distributed.

Parameter estimation is done using the Maximum Likelihood Estimation (MLE) method. The technical efficiency of each unit is calculated as:

$$TE_i = \frac{Y_i}{Y_i^*} = \frac{f(X_i; \beta).\ \exp(V_i - U_i)}{f(X_i; \beta).\ \exp(V_i)} = \exp(-U_i) \quad ...(2)$$

Since $Y_i < Y_i^*$, the TEi value lies in the range 0 to 1, where a value of 1 indicates full efficiency.

The SFA function model used in this study is expressed in the form of a Cobb-Douglas function as follows:

$$\ln Y = \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \beta_3 \ln X_3 + \beta_4 \ln X_4 + \beta_5 \ln X_5 + V_i - U_i \quad ...(3)$$

Where,

Y: Output (ton).

X_1: Harvested area (ha).

X_2: Subsidized ZA fertilizer (ton).

X_3: Subsidized NPK fertilizer (ton).

X_4: Subsidized granular organic fertilizer (ton).

X_5: Informal labor (%).

β_0, ..., β_5: Estimated parameters.

The SFA approach was selected because of the need to separate the influence of disturbances that cannot be controlled by farmers (*e.g*., weather, measurement

errors) from the inefficiency factors originating from input use. Its efficiency estimate more accurately reflects real field conditions.

Consistent with methodological advice in frontier modeling, this study first validated the SFA model, based on a Cobb-Douglas production function framework, before estimating it through multicollinearity testing among the input variables. The test for multicollinearity was conducted using the VIF value to investigate whether there is interference among the input variables that might lead to instability in the parameter estimates. Multicollinearity was considered when the VIF value was <10. In addition, the SFA model was also validated by estimating the gamma (γ) parameter, indicating the extent to which technical inefficiency explains deviations of output from a perfect competition. In contrast, random disturbances make up for this deviation. A γ value near unity indicates that the technical inefficiency component is playing a dominant role in output variation, providing even stronger support for the application of the frontier approach. This test serves to verify the consistency not only from a theoretical (SFA model) but also from a statistical aspect, in terms of the divergence of noise and technical inefficiency effects.

RESULTS AND DISCUSSION

Estimation of rice production function parameters

The estimation of rice production function parameters for 2018-2021 is presented in Table 2.

In addition to the estimated parameters shown in Table 2, the reliability of the Stochastic Frontier Analysis (SFA) model is evaluated through goodness-of-fit indicators. The Likelihood Ratio test (LR test) shows that the frontier model is significantly superior to the ordinary least squares (OLS) model, indicating that output variations do not only come from random disturbances, but are also influenced by technical inefficiencies. Furthermore, the obtained value of the gamma parameter (γ) is close to 1, which confirms that the most significant proportion of the output variation is caused by technical inefficiency and not noise. This confirms the appropriateness of using the frontier approach in analyzing the efficiency of Indonesian rice farming during the pre-crisis period. Thus, these results strengthen the interpretation of the parameters presented and ensure that the model used has statistical credibility, allowing it to clearly separate production inefficiencies from random factors in the rice production system.

Table 2 shows that the harvested area coefficient ranges from 1.17 to 1.28 and is statistically significant (t-ratio > t-table in all years). This suggests that increasing the land area directly increases rice yields. This finding is consistent with studies by Muhardi and Effendy (2021) and Tondi *et al*. (2025), which state that land is the dominant input in food crop production. The variations of coefficients from 2018 to 2021 suggest that the influence of harvested area on rice production is not stable and may be conditioned by multiple factors. Variability in the efficacy of harvested

Table 1: Descriptive statistics of the research variables.

Variables	Time (Year)							
	2018		2019		2020		2021	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Output (ton), (Y)	1,737,544.44	2,937,175.30	1,602,715.02	2,715,843.89	1,602,784.52	2,724,440.03	1,599,413.78	2,741,249.99
Harvested area (ha), (X_1)	334,800.57	513,836.45	314,178.02	477,455.97	313,315.32	481,450.75	306,507.36	484,917.56
ZA fertilizer (ton), (X_2)	29,563.86	87,794.12	28,907.66	86,743.99	24,331.17	65,652.20	20,613.44	64,458.27
NPK fertilizer (ton), (X_3)	78,735.68	130,958.54	68,837.81	120,484.01	79,895.37	134,619.47	80,131.06	135,214.98
Organic granular fertilizer (ton), (X_4)	21,604.62	67,467.32	22,262.38	68,591.41	19,453.18	56,235.15	15,535.06	45,831.48
Informal labor (%), (X_5)	86.17	10.14	84.75	11.74	86.56	10.07	86.67	9.94

area may arise from changes in weather patterns and irrigation availability, as well as the mobilization of new agricultural technologies between years (Silfiani *et al*., 2024). Moreover, extreme changes in governmental policies, such as land use, subsidies and market access, may have contributed to the uncoupling of harvested area and rice yield (Urrutia *et al*., 2017).

ZA fertilizer increases rice yield, as indicated by its positive coefficient in the rice production function from 2018 to 2021. This reflects the importance of nitrogen in rice production (Dhakal *et al*., 2019). The interannual variability in the impact of ZA fertilizer can be attributed to several environmental and management factors (Mirza *et al*., 2022; Vasuki *et al*., 2024). Soil conditions, weather patterns and water availability can influence the effectiveness of ZA fertilizer (Devi and Sivakumar, 2022). Additionally, the timing and method of fertilizer application as well as the rice variety cultivated can also influence the crop's response to ZA fertilizer (Elekhtyar *et al*., 2023).

The positive impact of NPK fertilizer was consistently observed throughout. It is an NPK fertilizer, in which N stands for nitrogen, P stands for phosphorus and K stands for potassium. Changes in the coefficients over time interfere with the fertilizer management. These differences would be attributed to the contributing factors of soil fertility status, climate variation and crop management measures on the efficacy of NPK fertilizers (Mirza *et al*., 2022; Devi and Sivakumar, 2022). The fertilizer applications (rates, timing and methods) can be adapted according to these factors (Elekhtyar *et al*., 2023), resulting in high nutrient use efficiency of rice and maximizing its output with minimal environmental footprint.

The high coefficient of granular organic fertilizers reflects that they have a significant positive effect on rice yield (Mirza *et al*., 2022). Soil structure, water retention and nutrient availability are enhanced by organic fertilizers, promoting optimal environmental conditions for rice plant development. Organic fertilizers that enhance soil physical, chemical and biological fertility levels have been proposed as the most suitable option to improve the long-term productivity of rice cropping systems (Devi and Sivakumar, 2022). Moreover, application of organic fertilizers decreases the dependency on synthetic inputs and thus reduces environmental impacts (*e.g*., GHG emission and water pollution) (Elekhtyar *et al*., 2023; Ekaria *et al*., 2025).

The positive sign of the informal labor coefficient reflects its contribution to rice production (Alam and Effendy, 2017). Informal labor, which includes family members and locally hired labor, is utilized to undertake a range of labor-intensive activities in rice production, such as planting, weeding, harvesting and post-harvest processing. Since the coefficient value is positive, increasing informal labor can enhance rice crop yield. In many regions with little advanced machinery, this non-capitalized labor is critical to conduct farming activities that are closely related to rice yield and productivity (Liu and Li, 2023). The findings regarding the significant contribution of informal labor to productivity increases indicate that the rural labor structure remains a crucial factor in Indonesia's rice production system. Therefore, this research can inform the government's design of inclusive mechanization policies-for example, by providing agricultural machinery and training to enhance the technical competence of informal labor and support gradual agricultural transformation (Custodio, 2025; Chandra and Walia, 2025). Evidence from Vietnam suggests that farmer efficiency (technical/profitability) improves when financial constraints and business shock risks are addressed simultaneously with the adoption of variety and technology-a finding relevant for intervention design in Indonesia (Nguyen *et al*., 2023). In Vietnam, a combination of small mechanization and training has also been found to increase the productivity of smallholder farmers. Thailand, on its part, has adopted strategies that promote public-private sector partnerships to enhance access to technology and market linkage. This comparison suggests that providing training programs and access to more affordable farm implements may be considered as potential strategies for improving the technical efficiency of rice production in Indonesia.

Impact of rice farming size on technical efficiency

The size of rice farming, expressed in terms of harvested area and technical efficiency, is presented in Table 3. The highest efficiency occurs in agricultural land with a harvested

Table 2: Estimation of rice production function parameters at different times.

Y	Time (Year)							
	2018		2019		2020		2021	
	Coefficient	t-ratio	Coefficient	t-ratio	Coefficient	t-ratio	Coefficient	t-ratio
Constant	-4.42		-5.84		-7.34		-3.23	
X_1	1.28*	19.02	1.23*	24.18	1.25*	22.43	1.17*	26.55
X_2	0.73*	8.57	0.67*	10.79	0.70*	10.27	0.89*	20.08
X_3	0.49*	11.90	0.46*	11.43	0.54*	13.09	0.59*	18.88
X_4	1.36*	36.48	1.33*	39.46	1.36*	40.55	1.41*	47.77
X_5	3.93*	9.35	4.25*	16.93	4.56*	14.06	3.63*	15.12
Sigma-squared	0.04		0.03		0.03		0.02	
Log-likelihood function	9.86		13.56		14.33		18.95	

Note: *= Significant at α = 1%.

area of 1,214,851.23-1,822,088.90 ha. Rice farming with a larger harvested area has higher technical efficiency.

Table 3 shows that technical efficiency increases alongside land area, from 0.842 to 0.915. This supports the theory of "returns to scale", where farmers with larger land areas have better access to technology, information and more efficient management (Muhardi and Effendy, 2021; Tondi *et al*., 2025). In contrast, small-scale farmers typically have limited access to essential agricultural inputs, including improved seeds, high-quality fertilizers and modern production tools (Olubunmi-Ajayi, 2024). Financial constraints and restricted access to credit hinder them from investing in productive technologies.

Impact of rice farming area on technical efficiency

The technical efficiency of rice farming by region is presented in Table 4.

The variation of technical efficiency in rice production and harvesting among the regions in Indonesia is presented in Table 4.

Table 3: Technical efficiency of rice farming based on harvested area.

Harvested area (ha)	Mean	Standard error	Minimum value	Maximum value
270.16-607,613.54	0.842	0.047	0.753	0.972
607,613.55-1,214,851.22	0.841	0.008	0.571	0.969
1,214,851.23-1,822,088.90	0.915	0.006	0.880	0.950

Table 4: Technical efficiency of rice farming by region.

Regions	Mean	Standard error	Minimum value	Maximum value
Aceh	0.919	0.004	0.911	0.926
North Sumatra	0.909	0.006	0.898	0.918
West Sumatra	0.873	0.006	0.864	0.885
Riau	0.821	0.010	0.806	0.841
Jambi	0.927	0.006	0.915	0.937
South Sumatra	0.880	0.015	0.851	0.902
Bengkulu	0.925	0.012	0.904	0.946
Lampung	0.904	0.013	0.888	0.930
Bangka Belitung Islands	0.784	0.075	0.640	0.893
Riau Islands	0.792	0.028	0.753	0.846
DKI Jakarta	0.950	0.011	0.939	0.972
West Java	0.930	0.010	0.917	0.950
Central Java	0.920	0.009	0.901	0.931
D.I. Yogyakarta	0.916	0.007	0.908	0.930
East Java	0.916	0.010	0.897	0.927
Banten	0.893	0.041	0.817	0.958
Bali	0.967	0.002	0.964	0.969
West Nusa Tenggara	0.873	0.015	0.843	0.893
East Nusa Tenggara	0.760	0.019	0.723	0.780
West Kalimantan	0.616	0.024	0.571	0.653
Central Kalimantan	0.632	0.013	0.610	0.654
South Kalimantan	0.750	0.027	0.702	0.795
East Kalimantan	0.771	0.005	0.761	0.777
North Kalimantan	0.859	0.023	0.832	0.904
North Sulawesi	0.860	0.022	0.833	0.903
Central Sulawesi	0.824	0.031	0.772	0.880
South Sulawesi	0.837	0.019	0.815	0.876
Southeast Sulawesi	0.750	0.024	0.724	0.797
Gorontalo	0.958	0.005	0.948	0.967
West Sulawesi	0.911	0.030	0.851	0.943
Maluku	0.785	0.029	0.730	0.826
North Maluku	0.803	0.058	0.724	0.916
Papua	0.789	0.041	0.707	0.837
West Papua	0.862	0.032	0.798	0.897

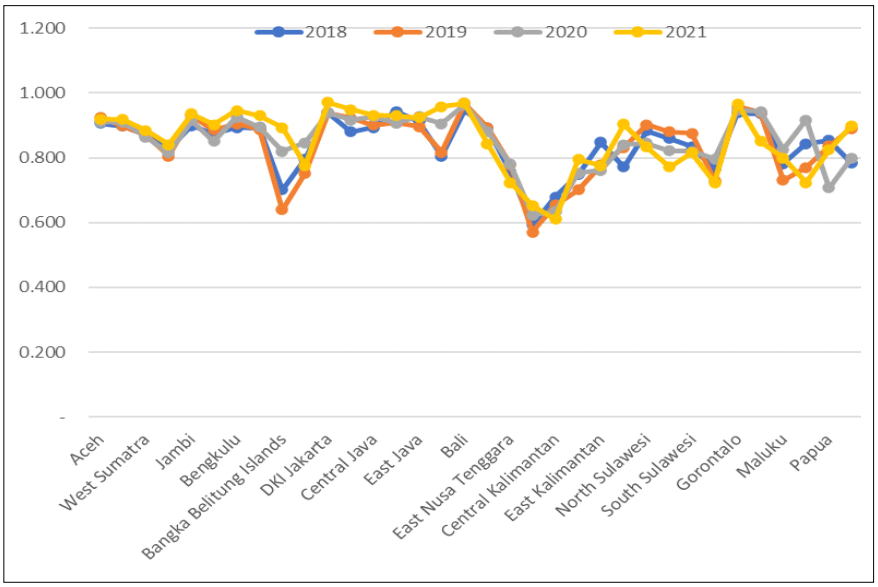


Fig 1: Development of technical efficiency in the time.

High technical efficiency regions

DKI Jakarta: Despite the province having relatively limited agricultural areas, rice production is maintained efficiently through its urban farming program and increasing land use density (Erissanti *et al*., 2021).

Bali: The developed stage of the Subak system is a key factor in its success, as it incorporates local wisdom with modern agricultural systems, enabling sustainable water management and resource distribution (Arisena and Dewi, 2017). Gorontalo has a good climate and fertile soil for growing rice (Iskandar and Jamhari, 2020).

Areas of low TE

West Kalimantan and Central Kalimantan face marginality, poor soil fertility, limited infrastructure and sociocultural constraints that result in inefficient agricultural cropping systems (Mustapa *et al*., 2019). The observation of such a discrepancy suggests that other factors may be influencing or hindering efficacy in each region. High-efficiency areas were more likely to be the product of agricultural practice, infrastructure and policy development. Concerning low-productive areas, it is expected that farmers will have restricted access to technologies, inputs, capital and information.

Dynamic analysis: Development of technical efficiency of the rice farming business in 2018-2021

A dynamic analysis of the technical efficiency of the rice farming business is presented in Fig 1.

As shown in Fig 1, technical efficiency increased in some areas between 2018 and 2021, but decreased in others. This is representative of the variegated agro-climate and praxis within the archipelago (Sumaryanto *et al*., 2023). Various factors, including rainfall distribution, soil type, temperature range, pests and disease pressure, influence rice productivity and the efficiency of resource utilization. Furthermore, efficiency can also be improved by the adoption of new technologies, growing practices and stronger policy support (Liu *et al*., 2020; Tondi *et al*., 2025).

CONCLUSION

All inputs analyzed-harvested area, ZA fertilizer, NPK, granular organic fertilizer and informal labor-showed significant, positive effects on rice production. Technical efficiency increases with the scale of the business: farmers with larger harvested areas exhibited higher efficiency. There is a significant disparity in technical efficiency between regions. Areas such as Bali, DKI Jakarta and Gorontalo exhibit the highest efficiency performance, while West Kalimantan and Central Kalimantan show low efficiency. The use of informal labor increases productivity proportionally, highlighting the need to improve the structure of the agricultural workforce. Fertilizer subsidies, particularly granular organic fertilizers, are crucial in enhancing technical efficiency. However, the existing subsidy policy has not optimally increased efficiency in all farmer groups, especially small farmers. Differences in efficiency between regions indicate the need for area-based policies that are tailored to local agroecological and socio-economic characteristics.

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Disclaimers

The opinions and conclusions presented in this manuscript are exclusively those of the authors and do not necessarily reflect the positions of their affiliated organizations. While

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Informed consent

All experimental procedures involving animals received prior approval from the Institutional Animal Care and Use Committee and all handling and care protocols adhered to the guidelines established by the committee.

Conflict of interest

The authors affirm that there are no conflicts of interest related to the publication of this manuscript. Furthermore, no external funding or sponsorship influenced any aspect of the research, including its design, data collection, analysis, publication decision, or manuscript preparation.

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