

## TRADE-INDUCED INEFFICIENCY IN ASEAN AGRICULTURE: A STOCHASTIC FRONTIER ANALYSIS OF TECHNICAL AND ENVIRONMENTAL EFFICIENCY

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### Abstract

**Background:** Agricultural systems in ASEAN face increasing pressure from rising food demand; however, prior studies predominantly assess technical efficiency without jointly considering environmental performance and trade-related inefficiency.

**Purpose:** This study evaluates technical and environmental efficiency in ASEAN agriculture and examines how trade dynamics influence this inefficiency.

**Design/methodology/approach:** A panel dataset covering ASEAN countries from 2003 to 2022 is analyzed using stochastic frontier analysis with a translog production function and time-varying inefficiency effects.

**Findings/Result:** The findings indicate that output growth is driven more by efficiency improvements and policy support than by input expansion. Capital contributes significantly to production, whereas land, labor, and fertilizer exhibit diminishing effectiveness. The average technical efficiency reaches 0.68, whereas environmental efficiency remains lower at 0.46, suggesting a persistent sustainability gap. In addition, net export expansion is associated with higher inefficiency when domestic capacity becomes insufficient.

**Conclusion:** Enhancing efficiency, technological upgrading, and environmental sustainability while aligning trade expansion with domestic capacity is essential for long-term agricultural performance.

**Originality/value (State of the art):** This study provides an integrated empirical assessment linking technical efficiency, environmental performance, and trade-related inefficiency in ASEAN agriculture, offering evidence of the alignment of trade expansion with sustainable productivity strategies.

**Keywords:** environmental efficiency, technical efficiency, trade efficiency, translog, time-varying

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## INTRODUCTION

The rapid growth of the global population has emerged as a major issue with profound implications for global food security (Salasa, 2021). This trend poses a critical challenge for the agricultural sector as the primary provider of food, which must simultaneously meet rising global demand while mitigating the environmental externalities associated with food production (Ibnu, 2024). Global population growth is projected to reach approximately nine billion by 2050 (Trakem and Fan, 2024). In parallel, global food demand is expected to increase by more than 50% over the same period, intensifying pressure on agricultural systems to enhance productivity without exacerbating environmental degradation. As the population size increases, the basic needs of individuals become more diverse and complex, a condition that disproportionately affects developing countries, which tend to face more pronounced challenges, particularly in key macroeconomic dimensions (Nirmala et al. 2022; Sukmawati, 2024).

Southeast Asia, commonly referred to as the Association of Southeast Asian Nations (ASEAN), is predominantly composed of developing economies. From a historical perspective, ASEAN was formally established through the Bangkok Declaration on August 8, 1967, and currently comprises ten member states: Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. The ASEAN region is characterized by a distinctive socioeconomic structure in which a large share of the population depends on agriculture for their livelihood (Rozci and Inti, 2023). Agriculture serves as a primary source of income and plays a crucial role in ensuring food security and supporting economic

stability across ASEAN member states (Rahman et al. 2024). Recent data indicate substantial heterogeneity in the contribution of agriculture to GDP across ASEAN countries, ranging from less than 1% in highly industrialized economies such as Singapore to over 20% in countries such as Myanmar, reflecting uneven structural transformation within the region (see Figure 1). The importance of the agricultural sector within the ASEAN economy is further reflected in its contribution to the gross domestic product (GDP). Figure 1 presents the agricultural GDP contributions of ASEAN member countries in 2023.

Despite substantial economic transformation in recent decades, agriculture remains a key component of ASEAN's socio-economic structure. This transformation has been marked by a structural shift away from agriculture toward the industrial and service sectors (Stads, 2020). Such changes reflect a common development trajectory in which developing economies experience declining shares of agricultural employment and GDP contributions as productivity increases and urbanization accelerates (Tricahyono and Wijaya, 2023). Countries that have undergone more advanced stages of economic transformation tend to reduce their dependence on agriculture, whereas economies with predominantly agrarian structures continue to rely heavily on agriculture as a central pillar of employment and income generation (Ali and Makhasin 2025). In this context, current research on agricultural modernization and a stronger focus on input efficiency and environmental externalities are integral to economic transformation and constitute fundamental prerequisites for achieving the Sustainable Development Goals (SDGs) (Abdulkerimov et al. 2024).

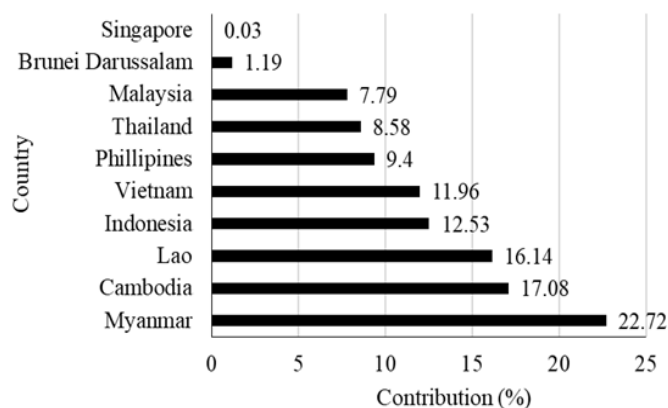


Figure 1. Contribution of the agricultural sector to Gross Domestic Product (GDP) in ASEAN Countries 2023 (Percent of GDP)

Despite ongoing efforts to promote ASEAN Good Agricultural Practices (ASEAN GAP), adoption rates and implementation effectiveness continue to face structural constraints in many member states. Countries that remain heavily dependent on traditional agriculture are particularly affected by low levels of mechanization, weak supporting infrastructure, and limited access to technical training and financial capital for farmers (Dewi et al. 2022; Tansuchat et al. 2022). Conventional production systems that rely on biomass burning and intensive chemical inputs have contributed significantly to greenhouse gas (GHG) emissions in the agricultural sector (Damu et al. 2023). These conditions indicate that productivity challenges in ASEAN agriculture are not solely related to resource availability but also to how efficiently and sustainably those resources are utilized within evolving production systems.

However, from an empirical perspective, the existing literature leaves several important gaps. Most prior studies have predominantly focused on technical efficiency, emphasizing input-output relationships without adequately incorporating environmental dimensions (Trakem and Fan, 2024). Although environmental efficiency has been explored in broader agricultural contexts, its application within ASEAN remains limited and often disconnected from conventional efficiency analysis (Bibi et al. 2021). In addition, the role of international trade, particularly export expansion, as a potential source of inefficiency has received relatively little attention, despite its growing influence on production incentives and resource allocation (Trakem and Fan, 2024). Consequently, there is a lack of integrated empirical evidence that simultaneously examines technical efficiency, environmental performance, and trade-related inefficiencies within a unified analytical framework.

A range of strategies can be adopted by ASEAN to address these challenges, one of which is the measurement of technical efficiency to ensure that actual input use reflects an optimal combination of production factors (Farrell, 1957; Battese and Coelli, 1988). As efficiency theory has evolved, environmental efficiency has been incorporated, reflecting the growing awareness of the ecological impacts of agricultural production processes. Consequently, the transformation toward modern and environmentally friendly agricultural practices is essential to support

sustainable farming systems, in which input use is both productive and efficient.

Inputs such as chemical fertilizers contribute to agricultural output but can also generate soil, water and air pollution when applied excessively. Reinhard et al. (1999) introduced an approach to measuring environmental efficiency based on environmentally detrimental inputs, defined as the ratio of the minimum required use of harmful inputs to their actual use, given a target level of output. This framework was further extended by Reinhard et al. (2000) to incorporate multiple environmentally detrimental variables, recognizing that environmental externalities in agriculture arise not only from fertilizer use but also from emissions. Emissions generated by agricultural activities represent uncompensated externalities that are often overlooked. As argued by Ayres and Kneese (1969), environmental pollutants can be viewed as by-products of production inputs because they physically originate from the energy and raw materials used in the production process. Therefore, emissions constitute input flows that are not fully transformed into economically valuable outputs. Accordingly, integrating technical and environmental efficiency dimensions is crucial for designing agricultural policies that simultaneously promote productivity and sustainability (Huang et al. 2023).

Agricultural inefficiency may also emerge as an unintended consequence of policy choices in several ASEAN countries, particularly through intensified trade liberalization (Trakem and Fan, 2024). From a theoretical perspective, the relationship between trade and efficiency is grounded in the Heckscher-Ohlin theory, which emphasizes specialization based on factor endowments and is further extended by the New Trade Theory, which highlights the role of economies of scale and market competition in enhancing productivity (Krugman et al. 2018). However, in developing economies, trade liberalization may induce inefficiency when domestic technological and institutional capacities are insufficient to support competitive adjustment. Although trade liberalization is often assumed to enhance efficiency, in the ASEAN agricultural context, it may instead reinforce structural inefficiencies by exerting market pressure to intensify production in pursuit of national economic targets, such as GDP growth, without adequate consideration of environmental sustainability. Since its establishment in 1967, ASEAN has served as the foundation for

regional economic integration, including the creation of the ASEAN Free Trade Area (AFTA) in 1992 and the ASEAN Economic Community (AEC), which was officially launched in 2015. The AEC has contributed positively to enhancing competitiveness and improving intra-regional trade efficiency, fostering greater market stability among ASEAN member states. The implementation of the AEC has been further reinforced by earlier agreements, notably the ASEAN Trade in Goods Agreement (ATIGA), which has been in force since May 2010 and was designed to eliminate tariff barriers and reduce trade transaction costs to expand the regional economic scale (Danendra et al. 2025). These developments underscore the importance of strengthening domestic production capacity and reinforcing intra-regional supply chains as long-term strategies for enhancing food security and reducing agricultural trade deficits (Mizik, 2021). Figure 2 illustrates the trends in agricultural export and import values in the ASEAN region over the past two decades.

Trade liberalization in the ASEAN agricultural sector has expanded market access and encouraged greater production efficiency among the member states. However, this openness also necessitates the optimization of production factors, such as land, labor, and capital, to increase output efficiently, while simultaneously posing challenges to environmental efficiency due to the intensified use of chemical fertilizers and energy inputs that may raise emissions. Agricultural trade liberalization can generate production inefficiencies when competitive market pressures encourage excessive input intensification.

When trade liberalization is not accompanied by efficiency-oriented management and regulatory frameworks, it may lead to resource misallocation and environmental externalities, thereby reflecting inefficiencies within liberalized agricultural systems (Trakem and Fan, 2024). In this context, it is essential to examine the extent to which agricultural production in ASEAN achieves technical efficiency, how far environmental efficiency is realized within existing production systems, and whether trade integration contributes to reducing or, conversely, exacerbating production inefficiency. From this background, the research objectives were to assess both technical and environmental efficiency in the ASEAN agricultural sector, while explicitly incorporating trade variables as determinants of inefficiency, and to examine whether trade liberalization ultimately enhances or undermines environmental efficiency.

## METHODS

The data employed in this study consist of secondary panel data, combining time-series and cross-sectional dimensions. The time-series component comprises annual data covering the period from 2003 to 2022. In terms of the cross-sectional dimension, the sample includes ten ASEAN member countries: Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. Further details regarding the data used in this study are provided in Table 1.

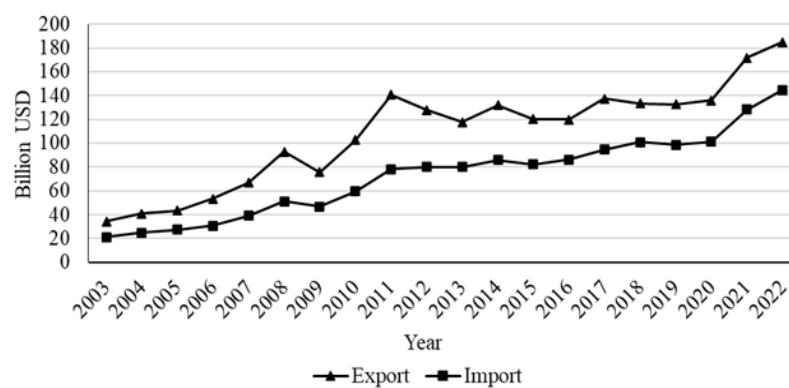


Figure 2. Aggregate Export and Import Values of the ASEAN Agricultural Sector, 2003–2022 (Billion US\$)

Table 1. Description of variables, measurement units, and data sources for estimating technical efficiency, environmental efficiency, and trade inefficiency in the ASEAN Agricultural Sector

Data Types	Symbol	Unit	Source
Gross Production Value of Agriculture	OUTP	US\$	World Bank
Agricultural Land Area	LAND	000 ha	FAO
Labor	LABR	000 persons	FAO
Capital	CAPT	US\$	FAO
Fertilizers Consumption	FERT	000 ton	FAO
Agricultural Emission	EMIS	Mt CO <sub>2</sub> e	FAO
Agricultural Export	EXPR	US\$	World Bank
Agricultural Import	IMPR	US\$	World Bank

Primary data were obtained from the FAOSTAT database, particularly from the Production Accounts, Inputs, and Emissions datasets, complemented by World Bank data for trade-related variables. Agricultural output (OUTP) is measured using the Gross Production Value in current thousand Standard Local Currency (SLC). Land (LAND) is represented by agricultural land area (000 hectares), while labor (LABR) is proxied by employment in agriculture based on ILO modelled estimates (000 persons). Capital (CAPT) is measured using Gross Fixed Capital Formation (GFCF) in agriculture, expressed in standard local currency, capturing investment in agricultural machinery and infrastructure. Fertilizer use (FERT) is defined as the total quantity of NPK nutrients applied (000 tons), and environmental pressure is proxied by agricultural emissions (EMIS), measured in CO<sub>2</sub> equivalent (Mt CO<sub>2</sub>e), based on AR5 standards.

Trade variables are derived from World Bank data, where agricultural exports (EXPR) and imports (IMPR) are expressed in US dollars, and net export is calculated as the difference between export and import values for each country-year observation. Prior to estimation, the dataset was harmonized to ensure consistency in units and comparability across countries, including the standardization of measurement units and treatment of missing values where necessary.

The analytical framework employed in this study is based on the transcendental logarithmic (translog) production function, which offers several advantages, most notably its greater functional flexibility relative to more restrictive production forms, such as the Cobb–Douglas specification. The translog model allows for variable elasticities of substitution among inputs and does not impose assumptions of constant returns to

scale or constant substitution elasticities (Reinhard et al. 2000). Unlike the Cobb–Douglas form, which imposes constant output elasticities and unitary elasticity of substitution, the translog specification allows for variable elasticities of substitution across inputs and does not impose restrictive assumptions on returns to scale. This makes it particularly suitable for capturing heterogeneous production structures across ASEAN countries. Equation (1) presents the production function specification adopted in this study:

$$\ln \text{OUTP}_{it} = \beta_0 + \beta_1 \ln \text{LAND}_{it} + \beta_2 \ln \text{LABR}_{it} + \beta_3 \ln \text{CAPT}_{it} + \beta_4 \ln \text{FERT}_{it} + \beta_5 \ln \text{EMIS}_{it} + 0.5\beta_6 (\ln \text{LAND}_{it})^2 + 0.5\beta_7 (\ln \text{LABR}_{it})^2 + 0.5\beta_8 (\ln \text{CAPT}_{it})^2 + 0.5\beta_9 (\ln \text{FERT}_{it})^2 + 0.5\beta_{10} (\ln \text{EMIS}_{it})^2 + \beta_{11} \ln \text{LAND}_{it} \times \ln \text{LABR}_{it} + \beta_{12} \ln \text{LAND}_{it} \times \ln \text{CAPT}_{it} + \beta_{13} \ln \text{LAND}_{it} \times \ln \text{FERT}_{it} + \beta_{14} \ln \text{LAND}_{it} \times \ln \text{EMIS}_{it} + \beta_{15} \ln \text{LABR}_{it} \times \ln \text{CAPT}_{it} + \beta_{16} \ln \text{LABR}_{it} \times \ln \text{FERT}_{it} + \beta_{17} \ln \text{LABR}_{it} \times \ln \text{EMIS}_{it} + \beta_{18} \ln \text{CAPT}_{it} \times \ln \text{FERT}_{it} + \beta_{19} \ln \text{CAPT}_{it} \times \ln \text{EMIS}_{it} + \beta_{20} \ln \text{FERT}_{it} \times \ln \text{EMIS}_{it} + v_{it} - [\alpha_{it} + \delta_1 \ln \text{NEXP}_{it} + \omega_{it}] \dots (1)$$

The estimation is conducted within a stochastic frontier analysis (SFA) framework, where the composite error term is decomposed into two components: a symmetric random error term ( $v_{it}$ ), assumed to be independently and identically distributed as  $N(0, \sigma_v^2)$ , capturing statistical noise and measurement error, and a one-sided non-negative inefficiency term ( $u_{it}$ ), which reflects technical inefficiency. Following Battese and Coelli (1988), the inefficiency term is assumed to follow a truncated normal distribution, allowing inefficiency effects to vary over time and be influenced by exogenous variables, including trade-related factors.

Regarding the inclusion of environmental variables, this study adopts the mass balance approach introduced by Ayres and Kneese (1969), which posits that production is a physical transformation process governed by the law of conservation of mass. Under this framework, emissions are not merely undesirable outputs but represent an inherent component of the production system, reflecting the transformation of material and energy inputs into both economic outputs and residual by-products. Consequently, emissions can be interpreted as a proxy for the intensity of material and energy use in the production process (Ebert and Welsch, 2007).

Maximum likelihood estimation (MLE) is used to infer population parameters from sample data using the likelihood function. To identify the inputs that significantly affect the agricultural sector's contribution to GDP, t-tests were conducted at the 5 percent and 10 percent significance levels. The hypotheses tested are formulated as follows:  $H_0$ : t-statistic < t-critical (inputs included in the model do not exert a statistically significant effect);  $H_1$ : t-statistic > t-critical (inputs included in the model exert a statistically significant effect).

In addition, the Likelihood Ratio (LR) test is applied to evaluate the adequacy of the estimated production function specification, particularly to distinguish whether the more parsimonious Cobb–Douglas form is sufficient or whether the more flexible translog specification provides a statistically superior representation. The statistical formulation of the LR test is presented in Equation (2).

$$\gamma = -2 \{ \ln[L(H_0)] - \ln[L(H_1)] \} \dots (2)$$

The term  $\ln[L(H_0)]$  denotes the log-likelihood value of the restricted Cobb–Douglas production function under the null hypothesis ( $H_0$ ) that the Cobb–Douglas specification adequately represents the production structure within the stochastic frontier framework. Conversely,  $\ln[L(H_1)]$  represents the log-likelihood of the unrestricted translog production function, with the alternative hypothesis ( $H_1$ ) asserting that the translog form provides a statistically superior representation of the production technology. Following the methodological assumptions proposed by Battese and Coelli (1988), the difference between these two log-likelihood values constitutes the LR statistic, which is assumed to follow a Chi-square ( $\chi^2$ ) distribution.

Furthermore, based on this operational framework, output elasticities of the production factors are subsequently calculated by aggregating the estimated regression coefficients of the linear input terms ( $\beta_{it}$ ), the quadratic interaction terms ( $X_j^2$ ), and the cross-input interaction terms ( $X_j \times X_k$ ) as formally expressed in Equation (3).

$$\delta \ln Y / \delta \ln X_{it} = \beta_{it} + \beta_{jj} \overline{\ln X_j} + \sum_{j \neq k}^k \beta_{jk} \overline{\ln X_k} \dots (3)$$

Technical efficiency is then estimated following the approach proposed by Battese and Coelli (1988). In this study, technical efficiency is measured as the ratio of observed output to the maximum feasible output, as defined by the stochastic production frontier, with the corresponding mathematical formulation presented in Equation (4). The results are subsequently illustrated through time-varying efficiency score visualizations.

$$TE_{it} = \exp(-u_{it}) = \exp[(z_{it}; \delta + \omega_{it})] \dots (4)$$

After obtaining technical efficiency estimates, environmental efficiency is calculated as the ratio of environmentally harmful input use at the technically efficient level to its actual observed use, conditional on a given level of output and constant conventional inputs. In this context, an environmental efficiency approach with multiple environmentally detrimental variables is employed to measure the efficiency of a particular production input that exerts negative effects on more than one environmental variable. This approach is considered relevant and appropriate for the present analysis (Reinhard et al. 2000). The formulation of environmental efficiency is presented in Equation (5).

$$EE_{it} = [ (\beta_4 + \beta_{14} \ln LAND_{it} + \beta_{24} \ln LABR_{it} + \beta_{34} \ln CAPT_{it} + \beta_{FERT,4} \ln FERT_{it}) + (\beta_5 + \beta_{15} \ln LAND_{it} + \beta_{25} \ln LABR_{it} + \beta_{35} \ln CAPT_{it} + \beta_{EMIS,5} \ln EMIS_{it}) - \{ 2 \times \beta_{FERT,FERT} \ln FERT_{it} + 2 \times \beta_{EMIS,EMIS} \ln EMIS_{it} + 2 \sqrt{\beta_z} \times U_{it} \} ] \div (\beta_4 + \beta_5) \dots (5)$$

Description:  $EE_{it}$  (Environmental efficiency of country  $i$  in year  $t$ );  $X_{12}, \dots$  (Interaction value of the estimated coefficients (coefficients  $\beta_1 \times \beta_2$ ) also applied for the next interaction variable);  $\beta_4$  (Coefficient of the FERT variable (fertilizer));  $\beta_5$  (Coefficient of the EMIS variable (agricultural sector emissions));  $U_i$  (Individual inefficiency component).

The operational framework of this study delineates a systematic causal pathway linking structural agricultural conditions in ASEAN to the measurement of technical and environmental efficiency and their trade implications. The framework begins with macro-structural drivers, namely population growth, rising food demand, and environmental pressures, which intensify the need for higher agricultural productivity while simultaneously constraining resource use. These pressures interact with production inputs at the on-farm level, including land, labor, capital, fertilizers, and environmentally detrimental variables such as emissions, within a stochastic frontier translog production structure. In this specification, conventional inputs and environmental pressures jointly determine output performance, while trade variables particularly net exports are incorporated as determinants of inefficiency to capture the role of regional integration and market openness.

The estimation process generates measures of technical efficiency, environmental efficiency, elasticity values, and returns to scale, which collectively reveal the production structure and scale characteristics of ASEAN agriculture. These empirical outcomes are subsequently interpreted within the broader context of policy disparities, institutional capacity, technological adoption, and trade integration frameworks across member states. Ultimately, the framework positions efficiency analysis not merely as a measurement exercise, but as an evaluative instrument to assess whether trade liberalization and structural transformation in ASEAN agriculture reinforce or constrain sustainable productivity, thereby informing policy refinement at both national and regional levels. The operational flow and research framework are presented in Figure 3.

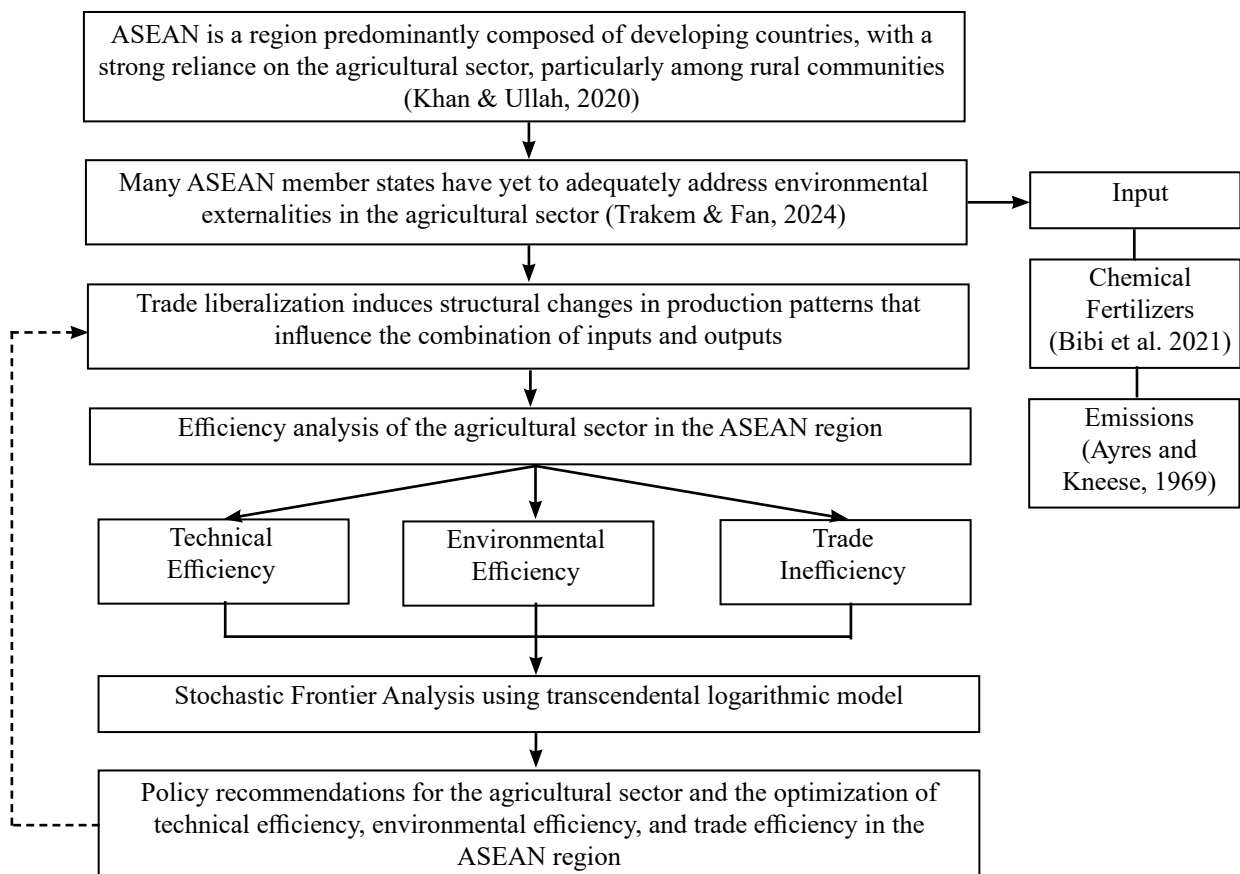


Figure 3. Operational flow and research framework from the research

## RESULTS

To determine the appropriate functional form, a Likelihood Ratio (LR) test is employed to compare the Cobb–Douglas and translog specifications (Coelli et al. 2005). The LR statistic of 337.38, exceeding the critical Chi-square value at the 1% level, leads to the rejection of the Cobb–Douglas model in favor of the translog specification. This confirms the suitability of the translog function in capturing input interactions and technological flexibility (Carrer et al. 2015; Ullah et al. 2017). Further testing indicates that the stochastic frontier model is preferred over OLS estimation. The LR statistic of 9.634 rejects the null hypothesis of no technical inefficiency ( $\sigma_u^2 = 0$ ) at  $\alpha = 0.025$ , supporting the presence of inefficiency effects and the appropriateness of the SFA framework (Kodde and Palm, 1986), based on one degree of freedom.

Within the stochastic frontier framework, rejection of the null hypothesis implies that deviations of observed output from the production frontier are not solely attributable to random noise, but are significantly driven by technical inefficiency. Consequently, the use of OLS is inconsistent and potentially yields biased estimates, as it fails to disentangle statistical noise from inefficiency effects. In contrast, the MLE approach enables the simultaneous identification and estimation of the production frontier and the inefficiency structure, as reflected in a well-defined log-likelihood value that is suitable for formal model testing. The estimated gamma parameter of 0.999 indicates that nearly all variation in output deviations from the frontier is explained by technical inefficiency rather than random error, thereby strongly justifying the use of an MLE-based stochastic frontier model. These findings suggest that agricultural production performance in the ASEAN region is predominantly determined by input efficiency structures, the quality of policy implementation, and trade performance. Accordingly, disparities in policy design and the implementation of Good Agricultural Practices (GAP) across ASEAN countries remain a critical factor shaping agricultural sector performance. The detailed results of the efficiency and inefficiency determinant analysis for the ASEAN agricultural sector are presented in Table 2.

Then, Elasticity calculations are conducted to represent the percentage response of agricultural output value to percentage changes in each input at their observed levels of use. Within the translog framework, interpretation is therefore based on the aggregate elasticity value for each variable. Accordingly, elasticity estimation incorporates all linear, quadratic, and interaction components embedded in the translog production function. In addition, the computed elasticities are used to evaluate the return to scale (RTS) condition, serving as an indicator of whether the agricultural production system in the ASEAN region operates under constant, decreasing, or increasing returns to scale. This assessment provides insight into whether the sector is already functioning at an efficient scale, experiencing diminishing productivity gains from input expansion, or still possesses the potential to achieve more-than-proportional output growth through simultaneous increases in inputs. Table 3 presents the estimated elasticity values and the corresponding return to scale conditions for each input considered in this study.

Based on the estimated output elasticities derived from the translog production function, the agricultural production structure in the ASEAN region is shown to be predominantly driven by capital as the principal determinant of output performance. The capital elasticity of 0.98 indicates that a 1 percent increase in capital input, *ceteris paribus*, translates almost one-for-one into a 0.98 percent increase in agricultural output value. This finding highlights strong dependence of ASEAN agriculture on physical investment and technology, including mechanization, irrigation infrastructure, and modern production equipment, all of which play a critical role in enhancing productivity at the regional scale. However, the capital-intensive nature of agricultural transformation may generate heterogeneous effects across countries, depending on differences in institutional capacity, access to credit, and the inclusiveness of technology adoption, thereby influencing the distribution of technical efficiency within the region (Trakem and Fan, 2024). In contrast, the relatively low land elasticity of 0.11 reflects limited role of area expansion in driving output growth. This result can be interpreted as evidence of constraints in the availability of productive land and a declining contribution of land expansion relative to technology-based intensification strategies (Sriboonchitta et al. 2017; Matsvai et al. 2022).

Table 2. Estimation results Stochastic Frontier Analysis (SFA) translog model on determinants of technical efficiency and inefficiency in the ASEAN Agricultural Sector

Variable	Parameters	Coefficient	Std. Error	P-Value
<b>Efficiency</b>				
Constanta	$\beta_0$	5.214	0.720	0.000 *
ln(land)	$\beta_1$	2.330	0.296	0.000 *
ln(labr)	$\beta_2$	-1.530	0.363	0.000 *
ln(capt)	$\beta_3$	1.032	0.170	0.000 *
ln(fert)	$\beta_4$	0.353	0.232	0.131
ln(emis)	$\beta_5$	-0.179	0.129	0.166
0.5[ln(land)] <sup>2</sup>	$\beta_6$	0.802	0.186	0.000 *
0.5[ln(labr)] <sup>2</sup>	$\beta_7$	-0.044	0.135	0.743
0.5[ln(capt)] <sup>2</sup>	$\beta_8$	-0.020	0.012	0.085 ***
0.5[ln(fert)] <sup>2</sup>	$\beta_9$	0.093	0.043	0.034 **
0.5[ln(emis)] <sup>2</sup>	$\beta_{10}$	0.091	0.064	0.159
ln(land) x ln(labr)	$\beta_{11}$	-0.373	0.123	0.003 *
ln(land) x ln(capt)	$\beta_{12}$	0.040	0.035	0.259
ln(land) x ln(fert)	$\beta_{13}$	-0.511	0.092	0.000 *
ln(land) x ln(emis)	$\beta_{14}$	-0.056	0.076	0.468
ln(labr) x ln(capt)	$\beta_{15}$	0.019	0.033	0.568
ln(labr) x ln(fert)	$\beta_{16}$	0.353	0.071	0.000 *
ln(labr) x ln(emis)	$\beta_{17}$	0.115	0.056	0.040 **
ln(capt) x ln(fert)	$\beta_{18}$	-0.017	0.018	0.369
ln(capt) x ln(emis)	$\beta_{19}$	-0.062	0.019	0.001 *
ln(fert) x ln(emis)	$\beta_{20}$	0.050	0.037	0.176
<b>Inefficiency</b>				
Constanta	$\delta_0$	0.358	0.129	0.006 *
ln(Nexp)	$\delta_1$	0.083	0.034	0.015 **
Sigma-squared		0.032		
Gamma		0.999		
Log likelihood		83.226		
LR Test		9.634		
Num. of Restriction		3		
Num. of iterations		37		
Num. of cross-sect		10		
Num. of time periods		20		
Total Observations		200		

Note: \*, \*\*, \*\*\* significant at the level of 1%, 5%, 10%, respectively

Table 3. Estimated output elasticities and returns to scale conditions derived from the translog production function in the ASEAN Agricultural Sector

Input Variables	Elasticity Score
Land	0.11
Labor	-0.25
Capital	0.98
Fertilizers	0.03
Emissions	0.20
Return to scale	1.06

The negative labor elasticity of  $-0.25$  does not reflect a statistical artifact, but rather captures a structural feature of agricultural production in ASEAN, where surplus labor and low marginal productivity remain prevalent. In many member countries, agricultural employment is characterized by disguised unemployment, limited skill upgrading, and slow technological adoption, such that additional labor input does not translate into proportional output gains and may even reduce overall efficiency. Within this context, the estimated coefficient is economically meaningful and consistent with the structural transformation literature, indicating that labor reallocation and productivity enhancement, rather than labor expansion, are central to improving agricultural performance (Náglová and Rudinskaya, 2021; Liu et al. 2022). Then the very small fertilizer elasticity of  $0.03$  indicates that marginal increases in fertilizer use contribute only minimally to output growth. This suggests that productivity enhancement strategies in ASEAN agriculture can no longer rely primarily on fertilizer intensification, but instead require improvements in technical efficiency, precision input use, and stronger integration of nutrient management policies with sustainable agricultural technologies. Within this context, the positive emission elasticity of  $0.20$  indicates that more intensive and emission-generating production activities remain positively associated with higher agricultural output, pointing to an existing trade-off between production expansion and environmental pressure. The elasticity should not be interpreted as emissions functioning as a conventional productive input. Instead, consistent with the mass balance framework (Ayres and Kneese, 1969), emissions are treated as an environmental input proxy reflecting the intensity of material and energy use embedded in the production process. In this context, higher emissions indicate more intensive use of environmentally detrimental inputs, which are simultaneously associated with higher output levels. Thus, the positive elasticity captures the underlying linkage between production intensification and environmental pressure, rather than implying a direct productive role of emissions. This result implies that the ASEAN agricultural production system has not yet fully transitioned toward a low-emission growth pathway, in which output gains can be achieved without a commensurate increase in environmental burdens (Nguyen et al. 2016; Trakem and Fan, 2024).

In aggregate terms, the estimated return to scale of  $1.06$  indicates that the ASEAN agricultural sector operates under increasing returns to scale, whereby a simultaneous 1 percent increase in all production inputs leads to a more-than-proportional increase in output. This condition implies that, given the current technological and institutional environment, the sector retains scope for achieving scale efficiency through farm consolidation, deeper value chain integration, and strengthened investment in technology and supporting infrastructure. Nevertheless, the sustainability of further scale expansion critically depends on the ability of ASEAN countries to improve technical efficiency, reduce reliance on emission-intensive inputs, and steer production growth toward pathways that are environmentally sustainable and socially inclusive (Bibi et al. 2020). Consistent with the identified scale properties of production, the assessment of ASEAN agricultural sector performance needs to be extended to the dimension of dynamic technical efficiency, as aggregate output outcomes are strongly influenced by changes in the production system's ability to utilize inputs efficiently over time. This dynamic perspective is presented in Table 4, which captures how technological change, policy evolution, and shifts in production structure affect the capacity of the ASEAN agricultural sector to transform inputs into output efficiently throughout the observation period.

Based on the estimation of time-varying technical efficiency for the ASEAN agricultural sector over the period 2003–2022, the results reveal substantial heterogeneity across countries and over time, with a regional average efficiency level of  $0.68$ . This finding indicates that, in aggregate terms, ASEAN agriculture still has the potential to increase output by approximately 32 percent through reductions in technical inefficiency alone, without requiring additional production inputs. In other words, most ASEAN countries are not operating on the maximum production frontier, implying that improvements in production management, technology adoption, and the effectiveness of agricultural policies could generate significant gains in sectoral performance.

At the country level, Thailand exhibits the highest average technical efficiency score at  $0.76$ , followed by Indonesia ( $0.73$ ), Malaysia ( $0.72$ ), and Vietnam and Cambodia (both at  $0.71$ ). The relatively high efficiency levels observed in these countries reflect a stronger capacity of their agricultural production systems to

convert inputs into output more optimally, which is consistent with higher rates of technology adoption, more effective input-support policies, and deeper integration into regional and global value chains. In contrast, Brunei Darussalam (0.50) and the Philippines (0.59) record the lowest efficiency scores, indicating structural constraints in the utilization of production factors. These constraints may stem from small-scale operations, fragmented production systems, and limited effectiveness of supporting policies and institutions. In the case of Brunei Darussalam, the limited orientation toward agrifood agriculture and a stronger focus on strategic plantation crops and natural resource sectors, particularly oil palm and hydrocarbons, play a significant role. For the Philippines, the predominance of small islands and a stronger orientation toward fisheries contribute to the fragmentation of the agricultural sector, complicating implementation, supervision, and

monitoring due to its archipelagic structure (Kea et al. 2016; Radlińska, 2023).

From a temporal perspective, most ASEAN countries exhibit fluctuations in technical efficiency over the observation period, rather than a fully linear upward trend. Improvements in efficiency during certain years reflect the positive impacts of agricultural modernization, policy reforms, and market expansion, whereas declines in other periods signal the vulnerability of the agricultural sector to external shocks, limited adaptive capacity to technological change, and inconsistencies in policy implementation. This pattern underscores that technical efficiency in the ASEAN region is inherently dynamic and strongly shaped by institutional quality, technological progress, and policy stability, rather than input availability alone (Chandel et al. 2022).

Table 4. Time-Varying Value of Technical Efficiency ASEAN Agricultural Sector

Year	BRN	KHM	IDN	LAO	MYS	MYR	FLP	SGP	THA	VNM	AVG ASEAN
2003	0.39	0.53	0.68	0.43	0.59	0.91	0.63	0.72	0.92	0.77	0.66
2004	0.41	0.56	0.62	0.46	0.68	0.90	0.61	0.90	0.86	0.89	0.69
2005	0.31	0.63	0.77	0.50	0.60	0.89	0.61	0.70	0.87	0.98	0.69
2006	0.50	0.68	0.61	0.54	0.85	0.93	0.57	0.66	0.84	0.83	0.70
2007	0.53	0.67	0.82	0.61	0.69	0.79	0.57	0.55	0.98	0.76	0.70
2008	0.57	0.69	0.82	0.60	0.83	0.66	0.56	0.70	0.84	0.87	0.71
2009	0.48	0.66	0.59	0.69	0.73	0.59	0.55	0.71	0.83	0.74	0.66
2010	0.52	0.78	0.75	0.84	0.90	0.53	0.55	0.53	0.83	0.75	0.70
2011	0.65	0.68	0.78	0.87	1.00	0.59	0.73	0.65	0.79	0.79	0.75
2012	0.58	0.71	0.82	0.78	0.84	0.54	0.70	0.62	0.70	0.69	0.70
2013	0.54	0.77	0.75	0.76	0.73	0.53	0.68	0.62	0.67	0.62	0.67
2014	0.64	0.92	0.68	0.85	0.61	0.68	0.66	0.64	0.68	0.63	0.70
2015	0.51	0.65	0.68	0.90	0.64	0.65	0.65	0.70	0.70	0.67	0.67
2016	0.51	0.62	0.85	0.83	0.62	0.69	0.61	0.71	0.82	0.66	0.69
2017	0.47	0.79	0.78	0.75	0.73	0.68	0.57	0.79	0.83	0.62	0.70
2018	0.44	0.80	0.73	0.77	0.57	0.62	0.54	0.64	0.76	0.61	0.65
2019	0.48	0.74	0.58	0.70	0.42	0.60	0.51	0.96	0.70	0.59	0.63
2020	0.44	0.76	0.74	0.67	0.61	0.70	0.55	0.78	0.72	0.61	0.66
2021	0.50	0.83	0.81	0.65	0.90	0.67	0.50	0.70	0.79	0.62	0.70
2022	0.53	0.80	0.85	0.49	0.87	0.92	0.47	0.81	0.01	0.55	0.63
Average	0.50	0.71	0.73	0.68	0.72	0.70	0.59	0.70	0.76	0.71	0.68
Rank	10	4	2	8	3	7	9	6	1	5	-

Description: BRN (Brunei Darussalam); MYR (Myanmar); KHM (Cambodia); FLP (Phillipines); IDN (Indonesia); SGP (Singapore); LAO (Laos); THA (Thailand); MYS (Malaysia); VNM (Vietnam)

Recent theoretical developments by Reinhard et al. (2000) emphasize the importance of estimating environmental efficiency to capture the extent to which agricultural production processes are not only technically efficient but also capable of minimizing environmental pressure. Environmental efficiency is defined as the ability of production units to reduce the use of environmentally harmful inputs or emissions without sacrificing the level of output achieved. The input-oriented environmental efficiency estimates indicate that the average environmental efficiency of the ASEAN agricultural sector over the period 2003–2022 is 0.46. This value suggests that, at the same level of output, ASEAN agriculture as a whole still has the potential to reduce environmentally damaging inputs particularly emission-intensive inputs by approximately 54 percent without compromising production levels. The range of environmental efficiency across countries is relatively wide, spanning from 0.21 to 0.52, reflecting pronounced heterogeneity in environmental management capacity across the region. Table 5 reports the environmental efficiency scores for the ASEAN agricultural sector.

Based on average time varying values of environmental efficiencies, Thailand ranks highest (0.52), followed by Indonesia (0.51) and Malaysia (0.50), indicating that these countries are relatively more capable of combining agricultural output achievement with the control of environmental pressures through more efficient technologies, better-managed cultivation practices, and relatively stricter input-use policies. Conversely, Brunei Darussalam ranks lowest (0.21), followed by the Philippines (0.41) and Lao PDR (0.47), suggesting that input use in these countries remains far from environmentally friendly relative to the regional best-practice frontier. From a dynamic standpoint, environmental efficiency in ASEAN exhibits moderate fluctuations without a consistent upward trend. Improvements in certain periods particularly in Thailand, Indonesia, and Vietnam reflect positive responses to policy reforms, technological adjustments, or market pressures favoring more sustainable production practices. However, declines in other years indicate that agricultural intensification is still frequently pursued through increased use of emission-intensive inputs, implying that productivity gains have not yet been fully aligned with environmental degradation control objectives (Tu et al. 2019).

The gap between technical efficiency (0.68) and environmental efficiency (0.46) reveals an imbalance in the agricultural transformation process, where productivity gains have been achieved more rapidly than the capacity to manage environmental pressures, implying that part of the observed efficiency improvements may be associated with relatively high environmental costs driven by intensive use of fertilizers and energy inputs. This condition reflects a transitional production regime in which output-oriented strategies still dominate, while the integration of sustainability principles remains partial, thereby underscoring the relevance of sustainable agriculture and green growth frameworks. In this context, Climate-Smart Agriculture (CSA) provides a coherent policy approach by promoting the efficient and controlled use of chemical fertilizers rather than their elimination, particularly through precision nutrient management based on the 4R principles right source, right rate, right time, and right place which aim to optimize productivity while minimizing environmental losses (Mishra et al. 2021; Yimer and Tarnawa, 2025). Furthermore, the integration of organic inputs and the adoption of advanced technologies, such as slow-release fertilizers and nitrification inhibitors, are essential to improving nutrient use efficiency and reducing emissions (Duan et al. 2023; Lakshani et al. 2023). From an institutional perspective, the persistence of low environmental efficiency also indicates that input subsidy policies remain largely volume-based, thereby encouraging overuse, whereas a shift toward practice-based incentives aligned with Good Agricultural Practices (GAP) is necessary to internalize environmental considerations into productivity enhancement strategies across ASEAN countries.

Accordingly, CSA emphasizes nutrient-use efficiency rather than mere increases in input intensity. Finally, based on the inefficiency function estimates from the translog stochastic frontier model reported in Table 2, the trade variable represented by net exports ( $\ln(\text{Nexp})$ ) exhibits a positive and statistically significant relationship with technical inefficiency in the ASEAN agricultural sector. The estimated coefficient on  $\ln(\text{Nexp})$  is 0.083 with a p-value of 0.015, indicating significance at the 5 percent level. The positive sign implies that an increase in net exports is associated with higher technical inefficiency, or implicitly, a decline in technical efficiency.

Table 5. Time-varying value of environmental efficiency ASEAN Agricultural Sector

Year	BRN	KHM	IDN	LAO	MYS	MYR	FLP	SGP	THA	VNM	AVG ASEAN
2003	0.16	0.37	0.47	0.30	0.41	0.63	0.44	0.50	0.64	0.53	0.44
2004	0.17	0.39	0.43	0.32	0.47	0.62	0.42	0.62	0.59	0.61	0.47
2005	0.13	0.44	0.53	0.35	0.42	0.62	0.42	0.49	0.60	0.68	0.47
2006	0.21	0.47	0.42	0.37	0.59	0.64	0.40	0.46	0.58	0.57	0.47
2007	0.23	0.46	0.57	0.42	0.48	0.54	0.39	0.38	0.68	0.53	0.47
2008	0.24	0.47	0.57	0.41	0.58	0.46	0.39	0.49	0.58	0.60	0.48
2009	0.20	0.46	0.41	0.48	0.51	0.41	0.38	0.49	0.58	0.51	0.44
2010	0.22	0.54	0.52	0.58	0.62	0.37	0.38	0.37	0.58	0.52	0.47
2011	0.28	0.47	0.54	0.61	0.69	0.41	0.51	0.45	0.55	0.55	0.50
2012	0.25	0.49	0.57	0.54	0.58	0.37	0.48	0.43	0.49	0.48	0.47
2013	0.23	0.53	0.52	0.53	0.50	0.36	0.47	0.43	0.46	0.43	0.45
2014	0.27	0.64	0.47	0.59	0.42	0.47	0.46	0.44	0.47	0.44	0.47
2015	0.21	0.45	0.47	0.62	0.45	0.45	0.45	0.48	0.48	0.47	0.45
2016	0.21	0.43	0.59	0.57	0.43	0.48	0.42	0.49	0.57	0.46	0.47
2017	0.20	0.55	0.54	0.52	0.50	0.47	0.40	0.55	0.57	0.43	0.47
2018	0.19	0.55	0.51	0.53	0.40	0.43	0.37	0.45	0.53	0.42	0.44
2019	0.20	0.51	0.40	0.48	0.29	0.42	0.35	0.66	0.48	0.41	0.42
2020	0.19	0.53	0.51	0.46	0.42	0.49	0.38	0.54	0.50	0.42	0.44
2021	0.21	0.57	0.56	0.45	0.62	0.46	0.35	0.48	0.55	0.43	0.47
2022	0.22	0.55	0.59	0.34	0.60	0.64	0.32	0.56	0.01	0.38	0.42
Average	0.21	0.49	0.51	0.47	0.50	0.49	0.41	0.49	0.52	0.49	0.46
Rank	10	4	2	8	3	7	9	6	1	5	-

Description: BRN (Brunei Darussalam); MYR (Myanmar); KHM (Cambodia); FLP (Phillipines); IDN (Indonesia); SGP (Singapore); LAO (Laos); THA (Thailand); MYS (Malaysia); VNM (Vietnam)

From an economic perspective, this result suggests that the expansion of net agricultural trade has not been fully accompanied by improvements in technological, managerial, and institutional capacity at the production level. As a consequence, pressure to meet external market demand may instead encourage inefficient input use (Sunge and Ngepah, 2019). This finding indicates that trade integration, when not supported by productivity-enhancing structures and effective technology transfer mechanisms, can generate technical efficiency distortions within the agricultural sector. The trade-related inefficiency results further imply that international trade and trade liberalization in the ASEAN region such as under the ASEAN Free Trade Area (AFTA) do not automatically function as determinants of technical efficiency. Rather, their impact critically depends on the quality of domestic production structures, farmer readiness, and policy support capable of translating market opportunities into sustained efficiency gains.

The empirical findings both corroborate and nuance prior evidence in the stochastic frontier and agricultural

efficiency literature. The rejection of the Cobb–Douglas specification in favor of the translog form is consistent with Trakem and Fan (2024), who argue that agricultural production technologies in heterogeneous regions are better characterized by flexible functional forms capable of capturing input interactions and non-constant elasticities. The dominance of capital elasticity and the presence of increasing returns to scale align with Sriboonchitta et al. (2017) and Matsvai et al. (2022), who document a growing role of mechanization and infrastructure investment in driving productivity gains in emerging agricultural systems. However, the negative labor elasticity contrasts with the conventional expectation of positive labor contribution in smallholder agriculture, as highlighted by Náglová and Rudinskaya (2021), suggesting that in the ASEAN context labor reallocation and skill upgrading are more critical than sheer labor expansion. Moreover, while Nguyen et al. (2016) and Trakem and Fan (2024) emphasize the persistent link between output growth and environmental pressure in developing economies, the relatively low environmental efficiency scores found here reinforce the argument of Bibi et al.

(2021) that productivity improvements in Southeast Asia remain insufficiently decoupled from emission-intensive practices. Finally, the positive association between net exports and technical inefficiency diverges from the trade efficiency hypothesis often discussed in Sunge and Ngepah (2019), indicating that, in ASEAN agriculture, trade expansion without parallel institutional and technological strengthening may generate adjustment costs and resource misallocation rather than immediate efficiency gains. Collectively, these comparisons position the present findings within the broader literature while underscoring the structural and policy-specific conditions that shape agricultural performance in the ASEAN region.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

The estimation results of the efficiency and inefficiency determinants using the stochastic frontier model indicate that the performance of the ASEAN agricultural sector is driven more by input-use efficiency and the quality of policy implementation than by the expansion of production factors. Capital emerges as the primary determinant of output growth, while the low land elasticity, the negative labor elasticity, and the marginal contribution of fertilizer use signal the limited effectiveness of land expansion and chemical input-based intensification strategies. The average technical efficiency score of 0.68 suggests substantial scope for performance improvement through better production management, enhanced technology adoption, and stronger institutional support. At the same time, the relatively low average environmental efficiency of 0.46 indicates that productivity gains have not yet been fully aligned with ecological sustainability objectives.

Regarding trade-related inefficiency, the estimation results show that agricultural trade in the ASEAN region has the potential to become a source of technical inefficiency when net export expansion is not accompanied by an increase in technological, managerial, and institutional capacity at the production level. The positive and significant coefficient of net exports on technical inefficiency indicates that trade liberalization is not an efficient determinant of efficiency, but depends on the domestic structure of each country. Overall, these findings suggest that harmonized policy implementation across ASEAN, grounded in

sustainable agriculture, Climate-Smart Agriculture, and green growth principles, can simultaneously enhance technical and environmental efficiency while ensuring more balanced and sustainable agricultural development in the region.

### Recommendations

To ensure that improvements in ASEAN agricultural performance do not continue to rely on factor expansion whose effectiveness is increasingly constrained, policy orientation should shift toward strengthening input-use efficiency through the accelerated investment in the adoption of appropriate technologies, modernization of farm management systems, and improvements in the quality of extension services and farmer institutions. Moreover, to prevent low environmental efficiency from remaining a persistent consequence of productivity growth, greater emphasis is required on the integration of sustainable production practices, the consistent implementation of Climate-Smart Agriculture (CSA), agronomically guided control of chemical input use, and the systematic internalization of environmental considerations into productivity-oriented policies at both national and regional ASEAN levels.

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