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CONTENTS

- 1 Quantile Insights Into the Role of Fertiliser, Harvesters and Estate Size in Shaping Oil Palm Fresh Fruit Bunches (FFB) Yield
Nur Nadia Kamil; Norhidayu Abdullah and Rosearnida Senawi
- 9 Economic Sustainability in the Palm Oil Sector: A Bibliometric Review Using R Studio
Wong Sing Yun



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QUANTILE INSIGHTS INTO THE ROLE OF FERTILISER, HARVESTERS AND ESTATE SIZE IN SHAPING OIL PALM FRESH FRUIT BUNCHES (FFB) YIELD

NUR NADIA KAMIL^{1*}; NORHIDAYU ABDULLAH¹ and ROSEARNIDA SENAWI¹

ABSTRACT

This study investigates the impact of fertiliser application, harvester availability and estate size on oil palm fresh fruit bunches (FFB) yield using quantile regression for Malaysian estates. Unlike traditional mean-based approaches, quantile regression allows for a deeper understanding of how these factors influence estates at different yield levels. The results reveal that fertiliser has a strong, positive effect across all yield quantiles, with diminishing returns at higher yield levels. Harvester availability plays a significant role, particularly for medium-yield estates. Estate size exhibits varying effects whereby small and medium-small estates underperform at lower quantiles and show modest improvements at higher quantiles. However, these upward shifts are only weakly significant and have limited effect sizes. These insights suggest while smaller estates may benefit from targeted support, the magnitude of their advantage at higher yield levels is modest. The findings contribute to optimising resource allocation and enhancing sustainability in Malaysia's palm oil industry.

Keywords: estate size, FFB productivity, quantile regression, yield determinants.

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INTRODUCTION

Palm oil stands as a cornerstone of the global vegetable oil market, accounting for 36% of global consumption and reaching over 75 million tonnes consumed in 2023 (Parveez et al., 2024). Malaysia plays a pivotal role in this industry, ranking as one of the leading producers alongside Indonesia and contributing over 25% of global palm oil production (Minal, 2025). However, the Malaysian oil palm sector faces a critical challenge which is the stagnation of fresh fruit bunches (FFB) yields. Despite advancements in planting materials and agronomic practices, national average yields have plateaued at 15–19 t ha⁻¹, falling significantly short of the potential 30–35 t ha⁻¹ (Henson, 2003; Parveez, 2024). This yield gap raises concerns about

the industry's future growth and sustainability, especially given the limited opportunities for plantation expansion due to land constraints and environmental regulations.

Previous study has explored various factors influencing FFB yield, including agronomic practices, environmental conditions and socio-economic constraints. Studies have highlighted the importance of fertiliser application, harvest intervals and nutrient management, but often with limitations. Brunelle et al. (2015) demonstrated the risk of diminishing returns and potential productivity losses from inefficient fertiliser use. De Vos et al. (2021) and Monzon et al. (2023) pointed to suboptimal yields among smallholders due to poor input management and harvest practices. However, existing studies often rely on mean-based models that assume uniform impacts across estates, overlooking the potential for differential responses based on yield levels (Kamil et al., 2024; Wing et al., 2021). Furthermore, the interaction between estate size and other factors,

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such as input effectiveness and socio-economic constraints, remains underexplored (Brandão & Schoneveld, 2021; Hadi et al., 2025; Webb et al., 2011).

This study aims to address these gaps by employing panel quantile regression to investigate the determinants of FFB yield across Malaysian oil palm estates. This approach provides a more differentiated understanding of the constraints and opportunities at varying yield levels. The goal is to inform more targeted productivity strategies and support evidence-based interventions in Malaysia's plantation sector. This article focuses specifically on estates reporting to Malaysian Palm Oil Board (MPOB) eCOST and e-submission systems between 2016 and 2021. While this allows for a robust, estate-level panel analysis, the study does not include smallholders or account for some agronomic and environmental variables, such as tree age profile, standing per hectare, rainfall and other related variables due to data limitations. Nonetheless, the findings offer timely insights into operational control that could help close the yield gap in this resource-constrained industry.

MATERIALS AND METHODS

Data on fertiliser expenses and estate size were obtained from the MPOB eCOST database, while yield data were sourced from the MPOB e-submission database. The data cover the period 2016-2021 and were aggregated annually for analysis. The MPOB eCOST is an online system that requires all MPOB licensees at the estate and mill levels to annually declare their cost of producing FFB and crude palm oil (CPO), ensuring high data coverage and reliability due to required reporting. Similarly, the MPOB

e-submission mandates that all MPOB-licensed estates declare their operational data such as area, FFB yield and number of harvesters, on a monthly basis for monitoring purposes. These reporting requirements, with penalties for non-compliance, contribute to the high data quality and reliability of the MPOB eCOST and e-submission portals.

Table 1 summarises the key variables for the study which include FFB yield ($t\ ha^{-1}$) as the dependent variable, with estate size (area in ha), harvesters per hectare and fertiliser expenses per hectare as the independent variables. Estate size was categorised into four groups, namely small estate (< 200 ha), medium-small estate (200 to < 500 ha), medium-large estate (500 to $< 1,500$ ha), and large estate ($> 1,500$ ha). Fertiliser expenses were measured on a per-hectare basis and later log-transformed to address skewness in the distribution.

To further explore the distributional characteristics of the dependent variable (FFB yield), a kernel density plot was generated (Figure 1). The horizontal axis represents FFB yield, while the vertical axis represents probability density that indicates the relative concentration of estates around specific yield values. Higher density values reflect a greater number of estates clustered near that yield. The figure highlights three key percentiles, the 25th percentile marks the threshold for low-yielding estates; the 50th percentile or median divides the sample in half; and the 75th percentile identifies the high-yielding group. Most estates yield around $18\text{--}22\ t\ ha^{-1}$ where the density curve peaks, while a smaller number achieve yields above $30\ t\ ha^{-1}$, resulting in a right-skewed distribution. This distributional pattern justifies the use of quantile regression, which enables the investigation of how explanatory variables affect yield differently across low-, medium- and high-performing estates.

TABLE 1. SUMMARY OF VARIABLES AND THEIR OPERATIONAL DEFINITIONS

Variable	Operational definition	Unit/scale	Source
FFB yield	Annual FFB output per hectare of planted area for each estate.	$t\ ha^{-1}\ yr^{-1}$	MPOB e-submission
	Additional note: Estates at $\tau = 0.25$ (low), 0.50 (medium) and 0.75 (high) yield quantiles.		
Estate size	Estate size is treated as a categorical variable, derived from continuous hectare values and then converted into dummy variables for regression analysis. Category of estate size: - Small: < 200 ha - Medium-small: 200 to < 500 ha - Medium-large: 500 to $< 1,500$ ha - Large: $\geq 1,500$ ha	Dummy variables (Large is the reference group)	MPOB e-submission
Harvester availability	Average number of harvesters in a year reported by the estate divided by planted hectares	Workers per hectare	MPOB e-submission
Fertiliser expenses (LFERT)	Natural-log of fertiliser cost per planted hectare	$\ln(RM\ ha^{-1})$	MPOB eCOST

Prior to the analysis, the dataset was reviewed for completeness and consistency. Missing values in key variables were imputed using median substitution in EViews to preserve the sample size and minimise potential bias. A small number of extreme and implausible values were also removed based on visual inspection and domain knowledge to improve the reliability of the estimates. Log-transformation was applied to fertiliser expenditure, as a result, some small positive values (e.g., RM0.05 ha⁻¹) appear as negative values in the descriptive statistics (e.g., $\log(0.05) \approx -3.0$). These do not indicate negative inputs but are a result of the transformation. This transformation allows coefficients to be interpreted in percentage terms, providing insights into relative changes. Table 2 below shows the data description before and after treatment, highlighting the improvements in data consistency following these adjustments.

Following these adjustments, a correlation analysis was conducted to assess the association between the variables and to ensure there were no multicollinearity issues that could influence the results. The analysis revealed a moderate positive correlation between yield and fertiliser expenses, suggesting that higher fertiliser usage is associated with increased yields. However, the results demonstrated a weak correlation between yield and the number of harvesters, while the correlation between yield and area is nearly zero, showing no linear relationship.

Model Specification and Estimation

This study employs panel quantile regression (PQR) to investigate the factors influencing FFB yield across Malaysian oil palm estates. Unlike ordinary least squares (OLS), which estimates the

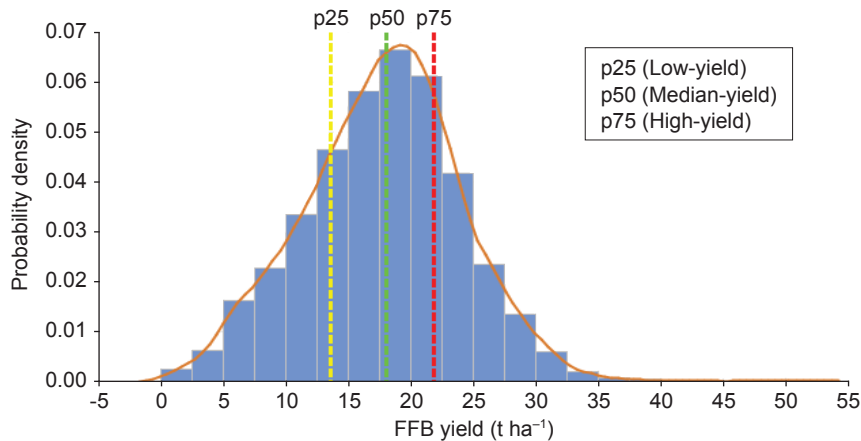


Figure 1. Kernel density distribution of FFB yield across estates.

TABLE 2. DATA DESCRIPTION BEFORE AND AFTER TREATMENT

Item	Raw data				Cleaned data			
	FFB yield	Fertiliser expenses	Harvester	Area	FFB yield	Fertiliser expenses	Harvester	Area
Mean	17.787	1,128.257	0.047	1,039.528	17.788	6.796	0.047	1,039.528
Median	18.093	1,023.610	0.041	389.000	18.093	6.931	0.041	389.000
Maximum	52.031	7,257.451	3.000	24,955.530	52.031	8.890	3.000	24,955.530
Minimum	0.527	0.035	0.017	0.000	0.527	-3.362	0.017	0.000
Std. Dev.	6.253	718.821	0.048	1,699.030	6.246	0.847	0.048	1,699.030
Skewness	-0.027	1.732	38.195	4.979	-0.027	-3.499	38.233	4.979
Kurtosis	3.090	9.571	2,204.431	46.100	3.096	27.427	2,208.898	46.100
Jarque-Bera	3.0766	1.31E+04	1.36E+09	5.50E+05	3.438	1.81E+05	1.37E+09	5.50E+05
Probability	0.215	0.000	0.000	0.000	0.179	0.000	0.000	0.000
Sum	1.20E+05	6.42E+06	317.468	7.01E+06	1.20E+05	4.58E+04	318.040	7.01E+06
Sum Sq. Dev.	2.63E+05	2.94E+09	15.453	1.95E+10	2.63E+05	4.84E+03	15.454	1.95E+10
Obs	6,730	5,688	6,730	6,744	6,744	6,744	6,744	6,744

average effect of explanatory variables, quantile regression allows the analysis of effects at different points in the yield distribution (i.e., low-, medium- and high-yield estates) (Koenker & Bassett, 1978; Kumar & Khanna, 2023). This is particularly valuable in the oil palm sector, where estates differ in land quality, management practices and other local factors that affect yield. PQR is well-suited for this analysis because it is more robust to outliers and heteroscedasticity in the dependent variable than OLS. It enables us to assess whether variables like fertiliser and labour have different levels of impact on lower- versus higher-yielding estates, which is an important insight for designing more targeted and efficient interventions.

By including estate size categories as dummy variables, the model captures how small, medium-small and medium-large estates compare to large estates across the conditional distribution of yield. The dependent variable in the model is FFB yield (YIELD), measured in t ha⁻¹ and further stratified into low-, median- and high-yield groups based on the 25th, 50th and 75th percentiles of the distribution, representing estate productivity. The key independent variables include fertiliser expenses (LFERT), representing nutrient application intensity. Harvesters per hectare (HARVESTER) proxy labour availability and operational efficiency. It is calculated as the total number of harvesters reported by each estate divided by its planted area. This metric reflects not only the supply of labour but also the estate's operational capacity to harvest FFB efficiently. A higher value indicates greater harvester presence relative to estate size, which can influence yield performance. Estate size is represented by dummy variables, with large estates serving as the reference category.

The general quantile regression model is specified as Equation (1):

$$\text{YIELD}_\tau = \beta_{0_\tau} + \beta_{1_\tau} \text{LFERT} + \beta_{2_\tau} \text{HARVESTER} + \beta_{3_\tau} \text{SMALL_ESTATE} + \beta_{4_\tau} \text{MEDIUM_SMALL_ESTATE} + \beta_{5_\tau} \text{MEDIUM_LARGE_ESTATE} + \epsilon_\tau \quad (1)$$

where, τ represents the quantiles of interest (e.g., 25th, 50th and 75th percentiles), β_τ denotes the quantile-specific coefficients, and ϵ_τ is the quantile-specific error term.

The model is specified based on the production theory, which suggests that output, which is the yield, is influenced by the inputs used in the production (fertiliser and labour) and the scale of operations (the area to proxy estate size). Fertiliser is essential in agriculture for replenishing soil nutrients (Barcelos et al., 2015; Henson, 2003), especially in oil palm plantations where it constitutes a major portion of production costs (Goh, 2005). Its pivotal role in achieving optimal yields makes

it a crucial variable in any econometric model analysing oil palm production. Ensuring adequate nutrients through fertiliser application supports healthy growth and maximises FFB production (Goh et al., 2003). For labour-intensive sector like oil palm sector, labour availability is a key driver for productivity. Estates with more harvesters per hectare are likely to achieve higher yields due to timely and efficient harvesting practices (Bakri et al., 2021; Parveez et al., 2024). Studies have shown that shorter harvesting intervals (10 days) lead to higher FFB yields compared to longer intervals (15 days) because delaying harvest can result in overripe fruits, increased losses from fruit detachment and lower oil quality (Mohanaraj & Donough, 2016). Meanwhile, for estate size, the existing literature suggests that small and medium-small estates tend to underperform relative to large estates (Zakaria et al., 2024). However, Cornia (1985) found that there is a strong negative correlation between farm size and land yields, with smaller farms generally having higher yields due to higher factor inputs and more intensive land use. Based on literature, the choice of quantile regression is deemed to suit the need to understand how fertiliser, harvesters and estate size impact FFB yields differently across estates performing at the lower (25th percentile), median (50th percentile) and upper (75th percentile) levels of productivity. This approach helps to understand the key productivity drivers across different yield levels, offering targeted recommendations for improving yield in low-performing estates and sustaining productivity in higher-performing ones.

RESULTS AND DISCUSSION

Table 3 summarises the quantile regression analysis for FFB yield determinants across oil palm estates at the 25th, 50th and 75th percentiles. The results indicated that fertiliser usage (LFERT) and harvester availability (HARVESTER_FILLED) are consistently positive and statistically significant across all yield levels, with varying magnitudes. This aligns with previous research highlighting the importance of these inputs in oil palm production (Barcelos et al., 2015; Henson, 2003). Medium-yield estates ($\tau = 0.50$) exhibit the strongest response to both inputs, suggesting that estates in this category are particularly responsive to improvements in fertiliser application and harvester availability. This might be attributed to factors such as better management practices or more favourable site-specific conditions in these estates. Low-yield estates ($\tau = 0.25$) also show substantial benefits from increased fertiliser usage and harvester availability, indicating potential resource constraints in this category. This finding supports previous studies

TABLE 3. QUANTILE REGRESSION RESULT (QRR)

Quantile	$\tau = 0.25$		$\tau = 0.50$		$\tau = 0.75$	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
C	-10.5631***	1.1230	-9.6281***	1.0801	-8.4395***	1.1428
LFERT	3.5288***	0.1603	3.7420***	0.1288	3.3752***	0.2177
HARVESTER_FILLED	30.8750***	7.5063	34.5902***	7.2754	28.7170***	5.9287
SMALL_ESTATE	-1.0750***	0.2611	-0.5299**	0.2234	0.4499*	0.2744
MEDIUM_SMALL_ESTATE	-1.0464***	0.2792	-0.4074	0.2568	0.5646**	0.2455
MEDIUM_LARGE_ESTATE	-0.1101	0.2800	0.0543	0.1964	-0.1044	0.2201
Pseudo R-squared	0.1299		0.1166		0.1017	

Note: *** - 1% significant; ** - 5% significant; * - 10% significant.

that have identified resource limitations as a major challenge for smallholder farmers and low-performing estates (De Vos et al., 2021; Monzon et al., 2023).

Estate size dummies reveal that small and medium-small estates underperform in low-yield conditions but exhibit modest improvements at higher yield levels. This suggests that while smaller estates may face disadvantages in resource-limited settings, their performance can improve under more favourable conditions or with appropriate support, although unobserved environmental and managerial factors may also contribute to these outcomes. This finding aligns with the literature on the heterogeneity of oil palm estates and the potential for smaller estates to achieve high productivity with adequate support (Zakaria et al., 2024). Delving into the specifics, fertiliser usage (LFERT) shows robust positive coefficients at all quantiles ($\tau = 0.25$: 3.5288; $\tau = 0.50$: 3.7420; $\tau = 0.75$: 3.3752), affirming its vital role in enhancing yield. The slightly lower impact at the upper quantile suggests diminishing marginal returns in already high-performing estates, which is consistent with previous findings on fertiliser response (Brunelle et al., 2015).

Harvester availability also demonstrates substantial effects, peaking at $\tau = 0.50$ (34.5902), indicating that medium-yield estates benefit most from improved mechanisation. This could be due to these estates having a higher capacity to utilise harvesters effectively compared to low-yield estates, while also not facing the same labour constraints as high-yield estates. The negative coefficients for SMALL_ESTATE (-1.0750) and MEDIUM_SMALL_ESTATE (-1.0464) at $\tau = 0.25$ reflect the challenges small estates face under resource-poor conditions, likely due to limited access to capital and technology (De Vos et al., 2021). In contrast, the positive shifts at $\tau = 0.75$ (0.4499 for SMALL_ESTATE and 0.5646 for MEDIUM_SMALL_ESTATE) imply that well-managed or supported smaller estates can outperform larger counterparts, potentially by leveraging their flexibility and adaptability (Zakaria et al., 2024).

While this study provides valuable insights into the role of fertiliser, harvesters and estate size in influencing FFB yield, it is important to acknowledge that other factors, such as environmental conditions, could also play a significant role (Kamil et al., 2024; Wing et al., 2021). However, due to data unavailability, these factors were not included in the analysis. Future research could explore the impact of environmental factors on FFB yield using more comprehensive datasets and potentially incorporate them into the quantile regression framework to gain a more holistic understanding of yield determinants.

Model Diagnostics and Robustness

In terms of the model fitness, the Pseudo R-squared values are relatively low across all quantiles, as it focuses on conditional quantiles rather than explaining the overall variance. The fit is slightly better for the lower quantile ($\tau = 0.25$), which indicates that the model explains the variation in yield better for low-yield estates compared to average or high-yield estates. Overall, the models provide meaningful insights but explain a limited portion of the variability in yield. The inclusion of additional explanatory variables, such as environmental qualities, may enhance to improve the variation in yield.

To evaluate the robustness of the quantile regression models, heteroscedasticity was first tested using the residuals of the OLS model. A likelihood ratio (LR) test was conducted, and the results confirmed the presence of heteroscedasticity (p -value < 0.05), indicating that the residual variance was not constant across observations. This violation of homoskedasticity can lead to inefficient standard errors and unreliable inference in standard models. To address this, the quantile regression models were re-estimated using bootstrapped standard errors, with 1,000 replications, to provide heteroskedasticity-robust estimates. The results in Table 4 confirmed that the significance of key coefficients remained largely consistent after the adjustment, reinforcing the robustness of the model.

TABLE 4. BOOTSTRAP RESULT

Quantile	$\tau = 0.25$		$\tau = 0.50$		$\tau = 0.75$	
Variable	Std. error	Bootstrap std. error	Std. error	Bootstrap std. error	Std. error	Bootstrap std. error
C	1.1229	1.0249	1.0801	0.9629	1.1428	1.5809
LFERT	0.1603	0.1422	0.1288	0.1288	0.2177	0.2177
HARVESTER_FILLED	7.5063	10.9592	7.2754	7.2754	5.9286	5.9286
SMALL_ESTATE	0.2611	0.2779	0.2233	0.2233	0.2744	0.2744
MEDIUM_SMALL_ESTATE	0.2791	0.2856	0.2567	0.2567	0.2455	0.2455
MEDIUM_LARGE_ESTATE	0.2800	0.2819	0.1963	0.1963	0.2200	0.2200
Pseudo R-squared	0.1299	0.1299	0.1166	0.1166	0.1017	0.1017

Notably, the fertiliser coefficient remained significant across all quantiles, with slight decreases in standard errors, indicating that the impact of fertiliser on yield is both strong and stable. For harvester, the standard error increased at $\tau = 0.25$ (from 7.5063–10.9592), reflecting variability in its impact on low-yield estates. The significance of estate size categories was also robust, although the bootstrap adjustment slightly reduced their significance at higher quantiles, particularly for $\tau = 0.75$. These findings confirm that heteroscedasticity did not bias the key conclusions and the bootstrap-adjusted models provide more reliable inference for policy recommendations.

Additionally, the Pseudo R-squared values remain the same across the bootstrapped and non-bootstrapped models, suggesting that the model's ability to explain yield variation at different quantiles is unaffected by bootstrapping.

Economic or Business Implications

The results of the quantile regression analysis provide critical insights into the determinants of FFB yield and their varying impacts across the yield distribution. Unlike OLS, which provides a single average effect, quantile regression reveals how these relationships differ for low-yield, medium-yield and high-yield estates, allowing for more targeted interventions and nuanced policy recommendations. In terms of fertiliser management, the study supports that fertiliser consistently has a strong and positive impact on yield across all quantiles, but its effect is slightly weaker at higher quantiles. For low-yield estates, the marginal benefit of increasing fertiliser usage is greater, suggesting that these estates are operating below optimal input levels. In contrast, higher-yield estates exhibit diminishing returns from additional fertiliser usage. This finding suggests that targeted fertiliser subsidies for low- and medium-yield estates can significantly improve their productivity and contribute to a more equitable distribution

of resources within the industry. Additionally, educational or training programs on fertiliser application and nutrient management practices could help reduce inefficiencies and encourage more sustainable use, particularly in smaller or less productive estates. These programmes could focus on soil testing, fertiliser recommendations based on site-specific conditions and the use of precision agriculture technologies to optimise fertiliser application.

In terms of harvesting, the number of harvesters per hectare was found to significantly impact yield across all quantiles, with the largest effect observed at the median quantile ($\tau = 0.50$). Low-yield estates also benefit substantially from increased harvester availability, indicating that mechanisation is a critical bottleneck for these estates. For high-yield estates, while the impact of harvesters remains positive, it is slightly diminished, suggesting that these estates may have already addressed labour constraints to a greater extent. To promote mechanisation and address resource constraints in low- and medium-yield estates, several interventions can be considered. These include providing access to affordable financing options for the acquisition of harvesting equipment, such as electronic cutters, which can enable smaller estates to adopt mechanisation and improve their harvesting efficiency. Other than that, the concept of shared harvester schemes can also be applied. Establishing co-operative schemes for the shared use of harvesters can reduce the financial burden on individual estates and promote resource sharing within the industry. In addition, investing in training programs for harvesters can enhance the effective utilisation of harvesting equipment and ensure its proper maintenance.

Estate size influences FFB yield in varying ways across performance levels. Small and medium-small estates generally yield less than large estates, particularly in the lower and middle quantiles. This disparity is likely due to limited

access to resources, such as capital, technology and skilled labour, which can hinder the adoption of optimal management practices and the achievement of economies of scale. While smaller estates may face disadvantages compared to larger estates, they have the potential to achieve high yields if they are well-managed, adopt efficient practices and receive appropriate support. This is supported by the positive (albeit modest) coefficients observed for small and medium-small estates at the upper quantile ($\tau = 0.75$), suggesting that with appropriate conditions, these estates can perform competitively. To address the challenges faced by smaller estates and unlock this potential, support programmes could be tailored to address structural constraints such as improving access to credit, high-yielding inputs, infrastructure and training. These efforts can help smaller estates invest in productivity-enhancing technologies and adopt more efficient, sustainable practices, ultimately improving both yield performance and resilience.

By recognising the heterogeneity of estates and tailoring support programs to their specific needs and constraints, policymakers can promote a more productive, equitable and sustainable palm oil sector. This will not only benefit individual estates but also contribute to the long-term economic growth and competitiveness of the Malaysian palm oil industry.

CONCLUSION

This study harnesses the power of quantile regression to unveil the complex, distributional effects of fertiliser usage, harvester availability and estate size on oil palm productivity. Findings demonstrate that while low- and medium-yield estates derive substantial benefits from increased fertiliser input and mechanisation, high-yield estates experience diminishing marginal returns, highlighting the necessity for precision in resource allocation. Notably, the divergent performance across estate sizes reveals that small and medium estates, despite inherent structural constraints, possess untapped potential when supported by targeted interventions. These insights carry profound implications for policymakers and industry stakeholders by suggesting a strategic shift from uniform input subsidies to a more tailored approach that prioritises support for underperforming estates, implements estate-specific policies and fosters collaborative efforts among government agencies, financial institutions and industry players. In essence, this study not only introduces a distribution-sensitive analytical framework but also provides a data-driven foundation for designing

policies aimed at reducing yield disparities and improving resource efficiency across estate sizes.

Although certain agronomic variables, such as palm age and stand per hectare (SPH), are important for understanding yield variation, they were not included in this study due to data harmonisation challenges and limited availability across estates. The absence of these variables may introduce omitted variable bias. For example, mature estates tend to apply more fertiliser and simultaneously achieve higher yields, which could partially inflate the observed fertiliser effect. Similarly, some low-yield estates may reflect over-aged stands awaiting replanting, rather than poor management. Future research could expand on this study by stratifying estates by planting age and, where possible, incorporating SPH to enable per-palm productivity analysis. Applying this quantile regression framework to a more agronomically detailed dataset would offer deeper insights into estate-level yield dynamics and policy targeting.

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ECONOMIC SUSTAINABILITY IN THE PALM OIL SECTOR: A BIBLIOMETRIC REVIEW USING R STUDIO

WONG SING YUN^{1,2*}

ABSTRACT

The growth of the global palm oil industry with the call to balance its significant economic contributions with pressing sustainability challenges has been a subject of debate for decades. In line with this pressing need, this study aims to examine the evolution of academic publications on economic sustainability in the palm oil industry through a bibliometric review of scholarly literature spanning from 1996 to 2025. The study analyses publication trends across different dimensions, including authorship, institutional affiliations, geographical distribution, and evolving topic trends. By assessing the trajectory of academic discourse, this study identifies key shifts from production-focused studies to research emphasising environmental impact mitigation, policy frameworks, and sustainable certification mechanisms. Findings from the review suggest that interdisciplinary collaborations have increased over time, reflecting a growing recognition of the complex interplay between economic growth and sustainability in the palm oil sector. In addition, this review highlights gaps in existing research, particularly concerning smallholder economic resilience and policy harmonisation. The study contributes to the academic and policy discourse by providing insights into future research directions that can support sustainable industry practices.

Keywords: bibliometric analysis, economic, palm oil, research trend, sustainability.

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INTRODUCTION

The palm oil industry plays a crucial role in the global agricultural economy, serving as a key source of edible oils and biofuels. However, the rapid expansion has raised concerns over environmental degradation, social implications, and economic sustainability (Hassan et al., 2025). The intersection economic growth and environment sustainability within this industry has become

a focal point for researchers and policymakers alike. As demand for palm oil continues to rise, ensuring a balance between economic growth and environmental responsibility is paramount (Parsons et al., 2020).

Sustainability in the palm oil sector is largely influenced by regulatory frameworks and voluntary certifications such as the Roundtable on Sustainable Palm Oil (RSPO). These measures aim to promote environmentally appropriate and economically viable production practices (Organisation for Economic Co-operation and Development [OECD], 2025). Several studies have highlighted that integrating sustainable practices, such as biogas energy utilisation and compost production, can enhance economic sustainability while reducing the carbon footprint of palm oil mills (Nasrin et al., 2024). Furthermore, sustainability certifications have demonstrated a positive impact on financial profitability. Hence, this provides

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economic incentives for companies to comply with stringent environmental standards (Hafizuddin-Syah et al., 2018).

Despite these efforts, challenges persist in ensuring a truly sustainable and economically viable palm oil industry. Some scholars (such as Ayompe et al. [2025], Mohd Noor et al. [2017] and Mukhlis et al. [2025]) argue that sustainability frameworks need further refinement to address the complex socio-economic dynamics of smallholder farmers and large-scale plantations. Additionally, evaluating the long-term financial benefits of sustainability initiatives remains an ongoing contending question (Mareeh et al., 2023). Given the critical need to balance palm oil industry growth with sustainability advocacy, previous study within this specific context has become highly debated. The findings from these past studies not only just providing the needed insight but to also provide future research direction.

A bibliometric review on economic sustainability in the palm oil industry is significant as it maps the trends, and research gaps in this field. By analysing existing literatures, the study can highlight evolving debates, policy implications, and technological advancements. Its contribution lies in identifying critical knowledge areas, guiding future research directions, and informing stakeholders-policy makers, industry players, and academics-on balancing economic growth with sustainable practices in palm oil production.

The remainder of the article will be structured as follows. The article will begin with the introduction that include a summary of the body of knowledge observed. Next, the research questions are pre-determined to ensure that the reviews are relevant to be used in addressing the questions in need. Subsequently, the methodology used in this article will be explicitly explained and illustrated. The output of the review analysis will then be reported in the results finding. A further discussion on the reviews finding will be provided subsequently. The final section concludes the research by contributing the future study directions and to highlight on the literature gap.

MATERIALS AND METHODS

For the purpose of this review, the search strategy of PRISMA (Preferred Reporting Items for Bibliometric reviews) was employed to gather relevant literature for the bibliometric analysis. The use of PRISMA will extensively scan all literature published on the subject to find answers to the clearly defined research question, and to that end use various inclusion and exclusion criteria to identify the reports to be included in the review, and then synthesise the findings (Yun et al., 2023). PRISMA provides a structured framework that enhances the clarity and reproducibility of bibliometric reviews, making it a widely accepted standard in the field (Page et al., 2021). The well-developed search strategy will be employed on the Scopus database in recognition of the credibility of Scopus as one of the largest academic literature databases with close to 50 million records of around 5,000 publishers (Grimaldi et al., 2017).

Using bibliometric, text-mining, and visualisation technologies, the following research questions (RQ) are used to illustrate the review process and activities. The methodology procedures utilised in this investigation, including the searching procedure, data collecting, extraction and analysis.

The search strategy begins by filtering and refining the literature by a combination of keywords. The preliminary search using the keywords of "Palm Oil" retrieved about 41,668 publications. By further filtering the search result with additional keyword of "Sustainability", the search retrieved about 2,460 publications. Further narrowing the search with another important key term of 'Economic Sustainability' has gathered 720 publications. By further restricting the article to English language publications only, 720 articles were obtained. *Table 2* illustrated the search inclusion and exclusion criteria used in refining the search for relevant publications. *Figure 1* showed the PRISMA strategy employed in searching, screening, and refining articles for the bibliometric review.

TABLE 1. RESEARCH QUESTIONS

No.	Research questions	Analysis protocol
1	What is the current state and trend of publication on the topic of Economic Sustainability in the Palm Oil Industry?	• Trend of Publications • Annual Scientific Production • Document by Subject Area • Document by Type • Annual Citations Per Year
2	How has the publication evolved on the topic of Economic Sustainability in the Palm Oil Industry?	• Document by Author • Document by Affiliation • Document by Country

TABLE 2. SEARCH CRITERIA

Scopus category	Searching criteria	No. of article
Keywords 1	"Palm Oil"	39,774
Keywords 2	"Sustainability"	2,436
Keywords 3	"Economic Sustainability"	720
Document type	All types of publication	720
Language	English	720

RESULTS AND DISCUSSION

What is the Current State and Trend of Publication on the Topic of Economic Sustainability in the Palm Oil Sector?

Figure 2 showed the trend of the publications screened and extracted from the Scopus database. The publications that meet all the inclusion criteria has been found spanning in between the years of 1996 to 2025 with the total of 720 documents. From Figure 2, the trend of publications has clearly illustrated a growing academic interest in the economic sustainability of the palm oil industry. The dataset reveals that the research activity on the topic of economic sustainability concerning palm oil industry has increased significantly in the past decade. This increase is likely attributable to heightened global awareness regarding the

environmental and economic challenges associated with palm oil production (Hilmi et al., 2025; Judijanto, 2025). The rising demand for sustainable palm oil, coupled with regulatory policies and consumer awareness, has spurred academic studies into this field (Chang et al., 2025; Narayanan et al., 2024).

Meanwhile, Figure 3 has presented the annual scientific production analysis, with clear rise of the number research publications per year. A closer examination of these trends clearly indicating an increasing interest of scholars on the economic sustainability of palm oil sector. The sharpest rise is observed between 2022 to 2024, with large number of papers being published in each of these years. This sudden surge can be attributed to global initiatives on sustainable agriculture, stringent environmental policies regulations, and industry-driven efforts to promote responsible palm oil production (Yeoh et al., 2025). This has further underscored how sustainability challenges from rapid palm oil expansion have prompted policy-driven strategic responses and need for inclusive green productivity, linking regulatory issues to sustainability research (Haryani et al., 2025). The growing scientific production highlights the increasing importance of economic sustainability in the palm oil sector within academic discussions.

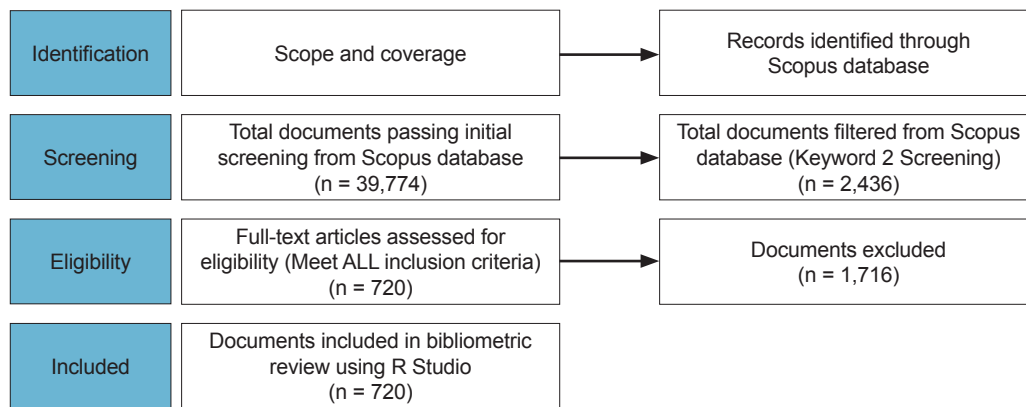


Figure 1. The PRISMA diagram used to find, screen, and select articles.

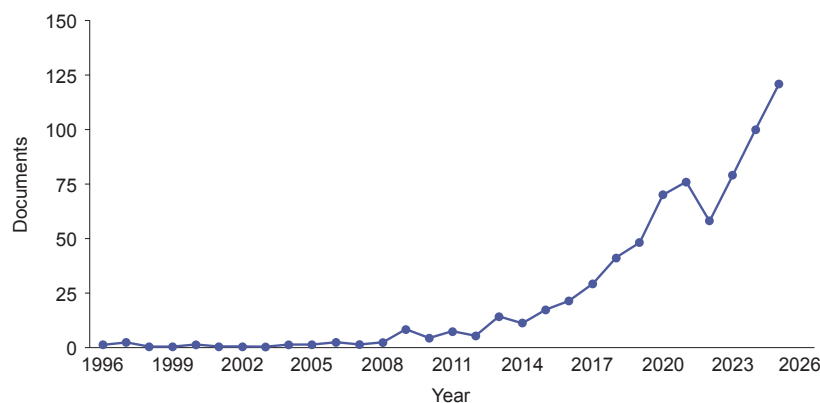


Figure 2. Trend of publications (1996–2025).

The distribution of documents by subject area, as depicted in *Figure 4*, underscores the multidisciplinary nature of research on economic sustainability in the palm oil sector. The majority of publications fall within environmental science (22.6%), which is expected given the pressing ecological concerns associated with palm oil production. A significant number of publications also fell under the field of energy (13.5%) suggesting that the palm oil sector's direct involvement in bioenergy, its environmental impacts linked to energy use and emissions, and the growing focus on renewable energy solutions. This explained the reason for palm oil sector researches to be frequently examined from an energy perspective that allows exploration of how it can become more sustainable and economically viable within the broader energy and environmental context. This is followed by large publications from the engineering field, revealing that the study of the economic sustainability in palm oil industry has been widely examined within engineering research domain. Agricultural economics (9.4%) is another prominent subject area, as researchers examined the financial feasibility and profitability of sustainable palm oil practices. Other disciplines such as social science (8.8%) similarly published in this research area, thus reflecting growing corporate interest in sustainable supply chain practices. This diversification in research disciplines implied

that the sustainability of palm oil is not only considered as an environmental issue but also poses significant economic and policy concern as well. The involvement of multiple fields suggests that addressing the sustainability challenges of the palm oil sector requires an interdisciplinary approach.

Figure 5 showed the analysis of the types of documents and revealing that journal articles constitute the largest proportion of published documents, followed by conference papers and reviews. The large percentage of journal articles (59.7%) signifies a strong emphasis on rigorous, peer-reviewed research that contributes to the academic body of knowledge on economic sustainability in the palm oil sector. Conference papers (comprised of 15.7%), on the other hand, indicate ongoing discussions and emerging research themes that are presented at international forums. Review articles (12.4%) play a critical role in synthesising existing research and providing comprehensive insights into past findings, gaps in the literature, and future research directions. The presence of various document types highlights the evolving nature of research in this field, with a combination of theoretical discourse and empirical analysis. This diversity also suggests that stakeholders, including policymakers and industry practitioners, can access research in multiple formats, aiding in the application of academic insights to real-world sustainability challenges.

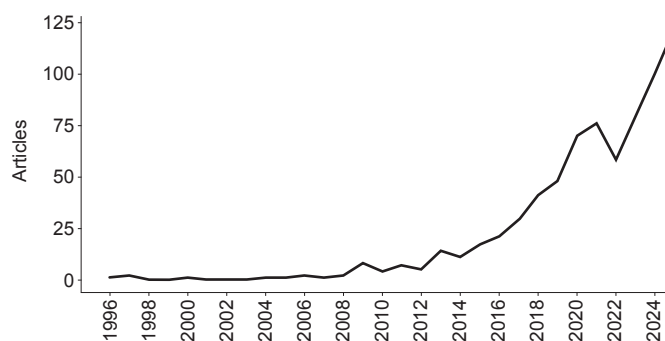


Figure 3. Annual scientific production (1996–2025).

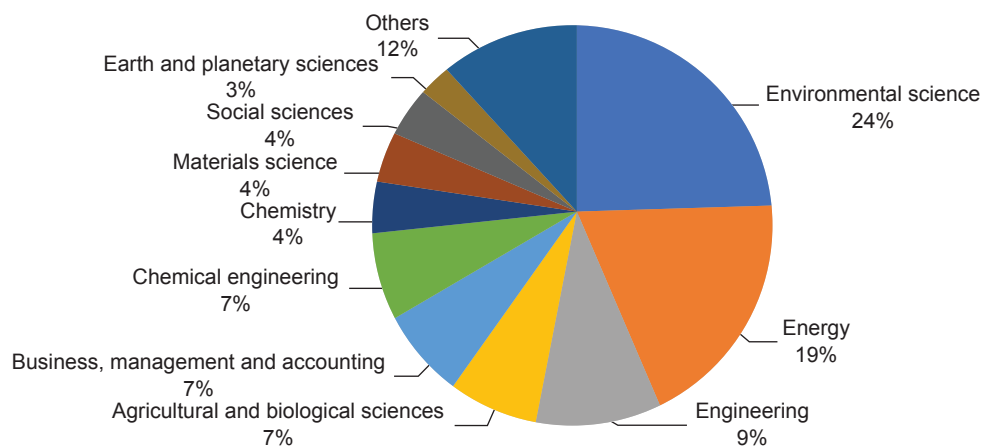


Figure 4. Documents by subject area.

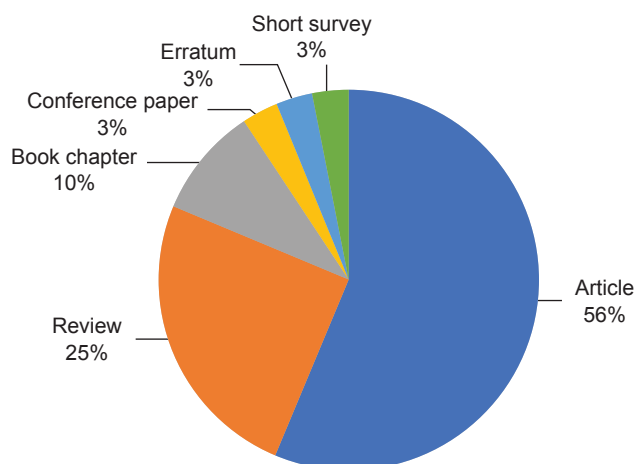


Figure 5. Documents by type.

Table 3 provides valuable insights into the impact of publications over time by demonstrating the citation analysis. The citation data indicates that older publications, particularly those from 2006 and 2018, have the higher mean citations per article, demonstrating their foundational role in shaping subsequent research. The relatively high citation count of publications from 2010 suggests that they contain influential findings or frameworks that have been widely referenced in later studies. In contrast, more recent publications, particularly those from 2023 to 2025, have lower citation counts due to their recent emergence in academic literature. This is a common trend in citation analysis, as it takes time for new research to be cited by subsequent studies. The variability in citation trends also reflects the differing levels of academic influence and relevance of publications in this field. Additionally, peaks in citation activity often coincide with periods of increased global discourse on sustainability, further reinforcing the importance of external socio-political factors in shaping research impact.

How has the Publication Evolved on the Topic of Economic Sustainability in the Palm Oil Sector?

Figure 6 showed the analysis of documents by author that indicated key scholars contributing extensively to the discourse on palm oil sustainability. Over the years, certain authors such as Lam, H. L., Lim, J. S., Hashim, H. have emerged as leading researcher, with a consistent increase in multi-author collaborations. Early research was dominated by a few prominent figures, but as awareness of sustainability concerns grew, a more diverse set of scholars entered the field. Several highly cited authors have concentrated on specific subtopics such as life cycle assessments (LCA), the socioeconomic impact of sustainable palm oil production, and corporate sustainability reporting. The increased collaboration among authors suggests

TABLE 3. ANNUAL CITATIONS PER YEAR (1996–2025)

Year	Mean TC per art	N	Mean TC per year	Citable year
2025	1.58	122	0.79	2
2024	7.14	100	2.38	3
2023	12.68	79	3.17	4
2022	16.98	58	3.40	5
2021	28.49	76	4.75	6
2020	23.47	70	3.35	7
2019	30.77	48	3.85	8
2018	42.44	41	4.72	9
2017	33.90	29	3.39	10
2016	39.29	21	3.57	11
2015	40.94	17	3.41	12
2014	66.18	11	5.09	13
2013	60.57	14	4.33	14
2012	85.80	5	5.72	15
2011	76.57	7	4.79	16
2010	146.50	4	8.62	17
2009	53.38	8	2.97	18
2008	33.00	2	1.74	19
2007	19.00	1	0.95	20
2006	98.50	2	4.69	21
2005	10.00	1	0.45	22
2004	0.00	1	0.00	23
2000	43.00	1	1.59	27
1997	20.50	2	0.68	30
1996	3.00	1	0.10	31

a multidisciplinary approach, integrating different perspectives from environmental science, social science, economics, and business. Additionally, the presence of co-authored papers between academia and industry professionals highlights the practical implications of research findings, demonstrating a trend towards applied research aimed at policy and industry implementation.

The subsequent Figure 7 showed the documents by affiliation covering the years 1996 to 2025. Academic institutions and research centers have

played a critical role in advancing knowledge on sustainable palm oil production. Universities from Southeast Asia, particularly in Malaysia and Indonesia were found to dominate the research landscape, reflecting the regional significance of the palm oil sector. Notably, affiliations with environmental and economic research institutes have increased, indicating an interdisciplinary approach to studying economic sustainability. For example, local Universiti Kebangsaan Malaysia (UKM) and Universiti Putra Malaysia (UPM) have consistently contributed to the discourse, focusing on sustainable farming practices, environmental impact assessments, and economic feasibility studies.

Meanwhile, Western institutions particularly from Europe and North America, have collaborated with Southeast Asian researchers, often examining the global implications of palm oil production on biodiversity and climate change. Government-affiliated research bodies and international organisations, such as the RSPO, have also contributed significantly to the research landscape. These affiliations highlight a growing convergence between academic research and policy-making, with universities and organisations increasingly focusing on policy interventions, certification mechanisms, and responsible production standards.

Figure 8 indicated the number of publications by countries. The analysis clearly illustrated that researches on palm oil sustainability was found to predominantly concentrated in countries with large palm oil production industries, such as Malaysia and Indonesia. Whereas, contributions from European and North American institutions have also risen, often focusing on the environmental impacts of palm oil supply chains and consumer-driven sustainability initiatives. Malaysia and Indonesia, as the world's leading palm oil producers, have seen a surge in research focusing on improving production efficiency while minimising environmental degradation. Studies from these countries emphasise sustainable land management, smallholder inclusion in Certified Sustainable Palm Oil (CSPO) programs, and the economic trade-offs of sustainability practices.

Meanwhile, European researches particularly from the Netherlands, Germany, and the United Kingdom, tends to investigate supply chain transparency, regulatory policies, and consumer perceptions of sustainable palm oil. The presence of European-funded sustainability initiatives in palm oil-producing countries has led to collaborative research efforts aimed at reducing deforestation and promoting eco-friendly production. Other countries, such as the United States and Australia, have contributed research on market dynamics, investment risks, and corporate responsibility related to the palm oil industry. The expanding

geographical scope of research suggests a growing recognition of palm oil's global economic and environmental impact, further reinforcing the need for international collaboration in addressing sustainability challenges. Although, Prasetyani et al. (2024) conducted a bibliometric analysis of palm oil business and environmental quality nexus, identifying trends related to environmental impacts and sustainability but they did not explicitly map to the economic sustainability topics. Similarly, Nasirly et al. (2024) conducted bibliometric review on life-cycle assessment in the palm oil industry systematically maps environmental sustainability research and methodological trends, yet does not foreground economic outcomes or economic performance dimensions.

By closely analysing the trend topics, the findings highlighted a shift in research priorities. Early publications primarily discussed economic feasibility and industry expansion, while more recent studies focus on sustainable certification systems, carbon footprint reduction, and alternative agricultural practices. The progression of research topics reflects both industry developments and external pressures from environmental organisations, governments, and consumers. Between 1996 and 2010, research centered around maximising yield efficiency, cost-benefit analyses, and global trade dynamics. Sustainability was often discussed as a secondary concern, with primary emphasis placed on economic expansion. As environmental concerns gained prominence, particularly following major deforestation incidents and criticisms from environmental NGOs, research from 2010 to 2020 increasingly addressed issues of sustainability certification, carbon emissions, and corporate social responsibility.

Post-2020, emerging topics have included blockchain for supply chain transparency, smallholder sustainability programs, and global policy alignment with environmental goals. The role of financial institutions in promoting sustainability through green financing mechanisms has also gained traction. Research now explores the integration of artificial intelligence (AI) and remote sensing technologies for monitoring deforestation and optimising sustainable palm oil practices. Moreover, interdisciplinary research is becoming more common, bridging economics, environmental science, and technology to propose innovative solutions for achieving economic sustainability. These trends indicate a future research trajectory that will likely emphasise regulatory compliance, technological advancements, and market-driven sustainability incentives.

The trajectory of research in this domain illustrates a growing commitment to balancing economic growth with environmental sustainability. Early research largely focused on

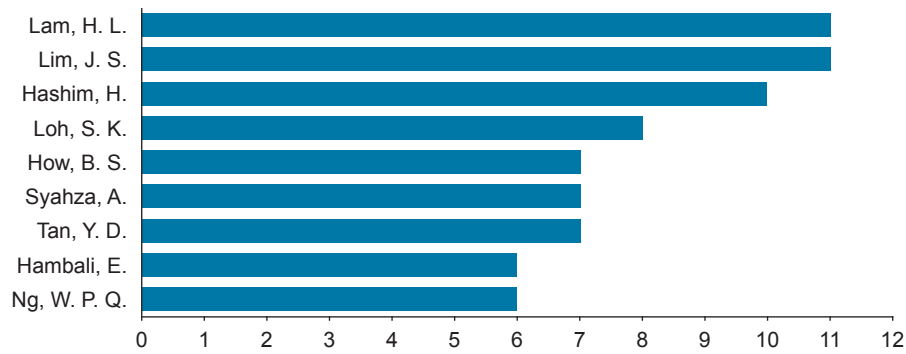


Figure 6. Documents by author (1996–2025).

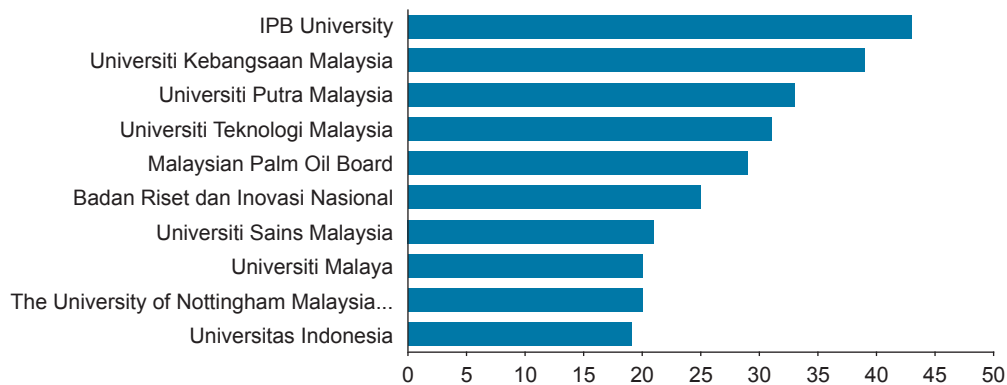


Figure 7. Documents by affiliation (1996–2025).

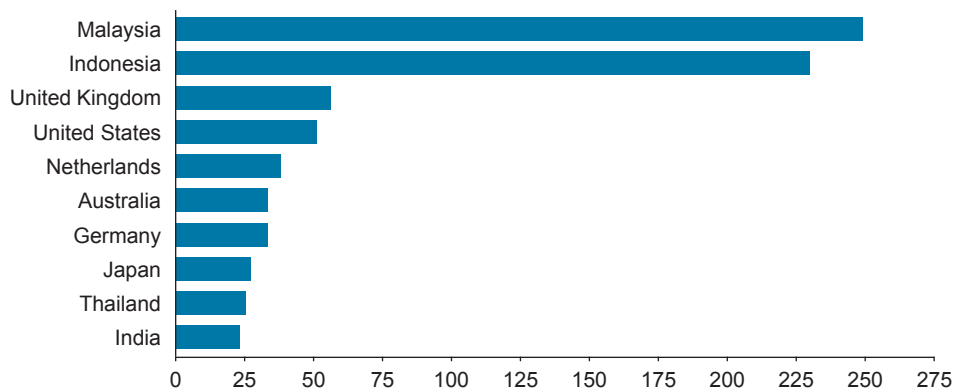


Figure 8. Documents by country (1996–2025).

optimising production efficiency and profitability, with minimal attention to sustainability concerns (Corley & Tinker, 2003). However, as environmental degradation, biodiversity loss, and climate change concerns became more pronounced, the research focus shifted towards sustainable agricultural practices, regulatory frameworks, and corporate responsibility (Gatti et al., 2019).

The increasing number of interdisciplinary collaborations indicates a shift from a purely economic analysis of palm oil production to an integrated approach that incorporates environmental and social factors (Meijaard et al., 2020). Studies on certification mechanisms, such as the RSPO, highlight the role of governance and

policy interventions in fostering sustainability (Npueng et al., 2023). Nevertheless, criticisms remain regarding the effectiveness and enforcement of these certification systems, particularly in ensuring smallholder participation (Ekaputri et al., 2025).

Within the economic aspect of sustainability, many past studies had been found to primarily focus on the economic feasibility and expansion initiatives which includes supply chain transparency, smallholder sustainability programs. This review therefore clearly reflected the evolution in research focus—from early works prioritising yield maximisation and trade expansion to more recent emphasis on certification, carbon footprint

reduction, and supply chain transparency. However, the economic implications of these shifts require deeper examination. For example, blockchain-based traceability solutions, while enhancing supply chain integrity, may introduce new technology adoption costs and create barriers for resource-constrained producers unless supported by targeted capacity-building programs and subsidised infrastructure (Abdullah & Alani, 2025; Bui & Le, 2025; Elkoraichi, 2025). In other words, the bibliometric has review underscores a pressing need to amplify the economic dimension of sustainability in the palm oil sector. While environmental science remains the dominant focus, only a modest share of literature addresses agricultural economics (6.8%) and business management (6.8%), pointing to an underutilised area of academic exploration.

Despite these advancements, gaps persist in understanding the long-term economic trade-offs of sustainability interventions. Future research should explore policy harmonisation, particularly aligning national sustainability policies with global climate agreements (Lambin et al., 2018). Moreover, more studies are needed to assess the economic resilience of smallholders under sustainability mandates and market-driven sustainability pressures.

CONCLUSION

This bibliometric review underscores the evolving nature of academic discourse on economic sustainability in the palm oil industry. The findings of this study reveal an increasing research focus on economic sustainability in the palm oil industry. The growing number of publications and citations highlights the academic community's commitment to addressing sustainability challenges. The interdisciplinary nature of the research indicates that sustainable palm oil production is a complex issue that requires insights from environmental science, economics, business, and policy-making.

Additionally, the industry's response to consumer demands for sustainable palm oil warrants further examination. The extent to which sustainability efforts translate into market advantages or economic trade-offs remains a crucial area for research. More longitudinal studies tracking the long-term economic benefits of sustainable practices will also contribute to a deeper understanding of how economic sustainability aligns with environmental sustainability. Overall, this bibliometric review underscores the importance of continued research and collaboration between academia, industry stakeholders, and policymakers. Strengthening the research-practice nexus can enhance policy recommendations and industry strategies, ultimately leading to a more economically sustainable palm oil sector.

Despite this expansion, the bibliometric evidence reveals several specific and underexplored research gaps. First, there is a notable lack of disaggregated economic viability studies, particularly those comparing independent smallholders and scheme smallholders. While smallholders are frequently mentioned in the literature, rigorous comparative assessments of cost structures, income stability, and long-term economic resilience across different smallholder models remain limited. This gap is especially critical given the central role of smallholders in global palm oil supply chains.

Second, although sustainability certification schemes feature prominently in keyword clusters, the literature shows limited empirical evaluation of their actual economic outcomes, such as productivity gains, profitability, and income distribution effects at the producer level. Similarly, research examining the economic impacts of regulatory frameworks tends to be conceptual or policy-oriented, with relatively few outcome-based or country-specific evaluations.

Third, the analysis indicates that technological innovation is often discussed in isolation, with insufficient integration of economic performance metrics. There is a lack of studies assessing whether digital tools, precision agriculture, or traceability technologies generate measurable economic returns alongside sustainability gains, particularly for small and medium-scale producers.

In addition, the findings point to a shortage of region-specific and comparative studies, especially across major palm oil-producing countries. This limit the understanding of how national contexts, governance structures, and market conditions shape the economic effectiveness of sustainability initiatives. Finally, while consumer demand for sustainable palm oil is frequently acknowledged, longitudinal research examining whether sustainability adoption translates into sustained market advantages or economic trade-offs remains scarce.

By identifying these granular, data-driven gaps, this bibliometric review contributes beyond mapping publication trends and offers a clearer agenda for future research. Addressing these missing areas can strengthen the research-practice nexus and support more targeted policy interventions and industry strategies, ultimately advancing a palm oil sector that is both economically viable and sustainable.

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