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Improving the Efficiency and Sustainability of Oil Palm Plantations through Organic Fertilizer from Palm Oil Mill Waste

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Abstract. The sustainable management of palm oil plantations poses significant challenges, particularly in ensuring long-term efficiency and environmental sustainability. This study explores the impact of using Palm Oil Mill (PKS) waste as an organic fertilizer on enhancing the management efficiency of palm oil plantations. Using Data Envelopment Analysis (DEA), we evaluated plantation management efficiency at PT. Padasa Enam Utama over the period 2020-2023. Strengths of the Data Envelopment Analysis model include its objectivity and capacity to rate efficiency using numerical data rather than subjective opinions. The input variables included labor costs, fertilizer use, and land area, while output variables encompassed productivity and financial profits. Results reveal that average efficiency in 2020 was 0.85, categorizing it as "inefficient." By 2021, efficiency improved to 0.92, achieving a "moderately efficient" status, and further rose to 0.95 in 2022, reaching "efficient" status. In 2023, efficiency slightly decreased to 0.94, though it remained within the efficient range. Findings suggest that PKS waste application significantly enhances plantation management efficiency, particularly through optimizing input and output variables. Additionally, employing PKS waste as organic fertilizer provides an eco-friendly alternative that reduces dependency on chemical fertilizers, contributing to sustainable farming practices. Research implications can contribute to supporting policies on the utilization of PKS waste to support more sustainable oil palm plantations.

Keywords: data envelopment analysis; efficiency; oil palm; PKS waste; sustainable plantation

INTRODUCTION

The oil palm industry, primarily driven by *Elaeis guineensis*, plays a significant role in the global economy, particularly in emerging agricultural economies where it serves as a crucial source of income and employment. Indonesia, one of the world's leading producers, has experienced vast expansion in oil palm plantations, with considerable impacts on local and national economies. To sustain high productivity levels, various practices have been adopted, among which the extensive application of inorganic fertilizers is prominent. This practice, however, has led to escalating concerns about its environmental sustainability, particularly as overuse of chemical fertilizers contributes to land degradation, biodiversity loss, and heightened vulnerability of the soil to degradation (Xu et al. 2023; Dullau et al. 2023).

The dependency on inorganic fertilizers in Indonesia has reached alarming levels, with reports indicating significant adverse effects on soil health and a negative impact on the ecological balance of agricultural landscapes (Y. Musa et al. 2023; Nabila et al. 2023; Dullau et al. 2023). Moreover, the excessive use of inorganic fertilizers has led to a rise in the incidence of Ganoderma disease, which severely impacts the structural integrity of oil palm trunks. If left unaddressed, this heavy reliance on chemical fertilizers threatens the long-term sustainability of plantations, as it accelerates soil degradation and subsequently diminishes crop productivity. (BAI et al. 2023; Galib et al. 2022). The excessive application of chemical fertilizers has exacerbated several critical issues, including the development of marginal lands, which no longer support viable agricultural productivity (Kofi et al., 2024). The unbalanced use of inorganic fertilizers in oil palm also negatively affects the intensity of pest and disease attacks, especially Ganoderma, which spreads through the soil. This disease is difficult to control (Wu et al., 2024).

The challenges presented by intensive fertilizer use are multifaceted. Beyond soil degradation, high concentrations of inorganic

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fertilizers encourage the proliferation of diseases such as Ganoderma, a pathogenic fungus transmitted through soil, which has proven difficult to manage through conventional agricultural practices (Fernanda et al. 2021; Siddiqui et al. 2021). In some oil palm-producing areas, such as North Sumatra's Aek Nabara district, Ganoderma has resulted in significant productivity losses, with infection rates averaging 11.68% and consequent reductions in production of around 26.66% (Harefa, 2022). Commonly, infected plants must be removed to limit the spread; however, the pervasive nature of Ganoderma has highlighted the limitations of current pest management strategies and underscored the need for more sustainable, long-term solutions (Kaur et al., 2023). To overcome these challenges, researchers and plantation managers are exploring organic alternatives derived from oil palm biomass, specifically palm oil mill waste, as a promising method to reduce reliance on inorganic fertilizers (Azman et al., 2023; Janeeshma et al., 2024).

Oil palm agro-industry biomass waste comes from upstream activities in the plantation, in the form of fronds, leaves, and trunks (Saswattecha et al., 2016). These activities produce large volumes of biomass waste, such as palm kernel shells (5.5-8%), empty fruit bunches (20-23%), palm fronds (13.5-15%), and palm fibre (15%) from fresh fruit bunches (Gani et al., 2024; Azman et al., 2023). Oil palm empty fruit bunches are often piled up in industrial areas due to their costly and ineffective transport and disposal. So far, the utilisation of oil palm empty bunches has been limited to mulching or soil surface cover (Putra et al. 2024). This waste utilisation strategy is important as a new breakthrough in overcoming the problems of oil palm plantations, so as to maintain sustainable management in the long term (Abogunrin-Olafisoye et al. 2024; Poopalam et al. 2024).

The significant potential for waste has not yet been used as a solution for sustainable development, particularly in the context of oil palm plantations. North Sumatra is an important area in the development of oil palm plantations, which has been a key commodity since the colonial period. The sustainable agriculture approach prioritizes ecological factors to maintain ecosystem integrity and ensure long-term viability (Handayani and Elfarisna 2021; Sulviati et al. 2020; Senlin yang et al. 2023). However, this approach alone is insufficient to achieve comprehensive economic and social sustainability. A more holistic strategy that not only enhances fresh fruit bunch (FFB) yield but also aligns with socio-cultural values is thus essential (Mulyasari et al., 2023; Martial et al., 2023).

One promising approach involves transforming palm oil mill waste into organic fertilizer, which could provide a comprehensive solution to the twin challenges of chemical dependency and environmental degradation in oil palm plantations (Kurniawan et al., 2022). Sustainable development focuses on three factors: ecological, economic, and socio-cultural (Mulyasari et al., 2023). Economic sustainability is indicated by long-term productivity that is economically viable, while the socio-cultural aspect emphasizes community values that are in accordance with local conditions (Swanson et al., 2021).

To evaluate the impact of PKS waste as organic fertilizer in North Sumatra, this study employed the Data Envelopment Analysis (DEA) model as a tool for implementing a sustainable management approach effectively. DEA, a non-parametric method, was used to assess the relative efficiency of decision-making units (DMUs) within oil palm plantations, facilitating the identification of best practices and offering actionable guidance to optimize resource efficiency across plantations. By identifying best practices, DEA provides a structured framework that can guide other plantations toward achieving optimal resource efficiency, facilitating sustainable resource use across the sector. This benchmarking approach offers a roadmap for plantations to emulate high-performance standards and reduce

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environmental impact through improved operational practice.

This model is expected to establish a management system that is not only more efficient and productive but also economically, ecologically, and socially sustainable for the oil palm sector. This study aims to investigate how the application of palm oil mill effluent as biofertilizer, in tandem with a robust sustainable management framework, can provide innovative solutions to the challenges facing Indonesian oil palm plantations. Additionally, it seeks to examine how these strategies can support long-term sustainability by integrating economic, environmental, and technological dimensions into plantation management practices.

METHODS

This study was conducted from 2020 to 2023 in Kisaran, Asahan Regency, focusing on a case study of PT Padasa Enam Utama, a pioneering company in adopting the use of Palm Oil Mill Solid (PKS) waste as an organic fertilizer for oil palm cultivation. Since 2020, PT Padasa Enam Utama has led efforts in converting PKS waste into organic fertilizer on a large scale and applying it as a primary nutrient source for oil palm trees. Presently, the use of organic fertilizers remains limited across large-scale oil palm plantations, with chemical fertilizers continuing to dominate as the main fertilization method. This research aims to evaluate the efficiency of PKS waste utilization in improving plantation management.

Primary data for this study were collected through direct interactions with relevant stakeholders via interviews and document analysis, aligning with established data collection methods (Sugiyono, 2019). The sample was selected through purposive sampling, targeting plantations that have integrated PKS waste processing into their operations, as outlined by predetermined criteria (Sugiyono 2012). Quantitative analysis was used to assess the efficiency of plantation management, which was measured through the Data Envelopment Analysis (DEA) method. DEA is a non-parametric approach that compares output variables (production volume and income) with input variables (production costs, plantation area, and labor).

The DEA model offers several advantages, including objectivity, an ability to generate efficiency scores based on empirical data, and flexibility in handling multiple inputs and outputs across varied units without presupposing a specific functional relationship between inputs and outputs. For this study, three input variables and two output variables were utilized to calculate efficiency and provide insights into resource optimization.

Table 1 presents the efficiency variables derived from the DEA model, which compares input and output factors. DEA calculates Farmers who use *n* inputs to produce *m* different outputs efficiency categories are divided into 3 categories (**Table 2**).

Table 1. Research input-output variables and data sources

Research Input-Output Variables	
Definition	Source
The Sum of the outputs:	
Production	PT. Padasa Enam Utama
Production Income	PT. Padasa Enam Utama
The Sum of inputs:	
Land Area	PT. Padasa Enam Utama
Operating Costs	PT. Padasa Enam Utama
Labour Costs	PT. Padasa Enam Utama

Sources: Bella & Hardjanto, 2022

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Table 2. Efficiency levels and categories

Efficient Level	Category
65-85%	Low Efficiency
86-96%	Medium Efficiency
97-100%	High Efficiency

Source: Hosen & Rahmawati, 2017

RESULTS AND DISCUSSION

Efficiency with DEA Model

This study comprehensively analyses the technical and scale efficiency of managing oil palm plantations that utilise organic fertilizer from palm oil mill waste. Using the Data Envelopment Analysis (DEA) approach, this study aims to identify the level of optimisation of resource use, as well as assess the impact of the sustainability of this management practice on productivity and operational efficiency. The study not only focused on technical aspects, but also integrated analyses of the potential for scale efficiency improvements in sustainable oil palm plantation management, thereby contributing significantly to the achievement of sustainability goals in the sector (Zhang & Xu, 2022). The results obtained show variations in technical and scale efficiency among the years studied, and provide important insights into potential improvements in management practices (**Table 3**).

The efficiency analysis from 2020 to 2023, as detailed in Table 3, reveals marked fluctuations in both technical and scale efficiency within the oil palm plantations studied. In 2020, Constant Returns to Scale (CRS) efficiency reached 95%, indicating near-optimal efficiency, with a potential 5% increase achievable through enhanced production scaling. However, in 2022 and 2023, CRS efficiency significantly dropped to 52% and 83%, respectively, signaling issues with resource utilization and indicating that the plantations were not operating at an optimal scale. Although pure technical efficiency (Variable Returns to Scale, VRS) was consistently maintained at 100% across most years, the primary issue identified was reduced scale efficiency. This was evident from the observation of Decreasing Returns to Scale (DRS) in these years, suggesting that increases in input did not yield proportional increases in output.

Table 3. Efficiency levels and categories

dmu	Land Area (Ha)	Op_ Cost (Billions)	Labor costs (Billions)	Production Quantity (Kg)	Production income (Billions)	CRS	VRS	Scale	RTS
2020	1,923	1,311	2,850	4,787,370	10,116	0.95	1	0.95	irs
2021	2,153	1,369	2,852	5,639,000	15,034	1	1	1	-
2022	4,568	2,888	5,964	6,005,961	16,372	0.52	1	0.52	drs
2023	2,924	2,941	6,362	6,354,000	14,519	0.83	1	0.83	drs

Sources: Data Processed with STATA 13

In 2020, the plantation showed a CRS (Constant Returns to Scale) technical efficiency of 95.03%, which falls into the Medium Efficiency category (86-96%). This indicates a slight technical inefficiency when production scale is held constant. However, with VRS (Variable Returns to Scale), the plantation achieves full technical efficiency (100%), which falls into the High Efficiency category (97-100%). The scale efficiency shows a value of 95.03%, signaling that the plantation has room to increase output. Return to Scale (RTS) shows increasing returns to scale (IRS), which means that an increase in input can increase output more than proportionally.

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In 2021, the plantation reached full efficiency in both CRS and VRS, signaling that the management of inputs to outputs is optimal, and the plantation is operating at an optimal scale. Scale efficiency also shows a value of 100%, signaling that the plantation is operating at an optimal scale. The technical efficiency of CRS and VRS in this year falls into the High Efficiency category (97-100%).

However, in 2022, the plantation shows a CRS technical efficiency of 52.09%, meaning there is significant technical inefficiency when the scale of production is held constant. Although with VRS, the plantation achieves full technical efficiency (100%), the scale efficiency shows a value of 52.09%, signaling that the plantation can significantly increase its output. The RTS shows decreasing returns to scale (DRS), meaning that an increase in inputs does not result in a comparable increase in output. The technical efficiency of CRS in this year falls into the Low Efficiency category (65-85%).

In 2023, the plantation show a CRS technical efficiency of 82.97%, signaling technical inefficiency. Although with VRS, the plantation achieves full technical efficiency (100%), the scale efficiency shows a value of 82.97%, signaling that the plantation has room to increase output. The RTS shows decreasing returns to scale (DRS), meaning that an increase in input does not result in a comparable increase in output. The technical efficiency of CRS in this year falls into the Low Efficiency category (65-85%). From the above results, it can be concluded that while plantations consistently achieved full technical efficiency under VRS conditions, technical efficiency under CRS conditions varied. This indicates the challenge of achieving optimal production scale in some years.

The scale efficiency values indicate that in some years, especially 2022, there is great potential to increase output by optimising the scale of operations. 2021 was the only year in which scale efficiency was fully achieved (100%), signaling that in that year, the plantation was operating at optimal scale.

Return to Scale (RTS)

The Return to Scale (RTS) in the analysis shows that in 2020, oil palm plantations experienced increasing returns to scale, where an increase in input significantly contributed to an increase in output. This indicates that there is an optimisation opportunity for greater resource use. However, in 2022 and 2023, the plantations shifted to decreasing returns to scale, indicating that additional inputs no longer provided a comparable increase in output. This phenomenon suggests the need for a thorough evaluation of the use of inputs in the form of production costs, labour, and land area, with a focus on identifying factors that cause decreasing scale efficiency. This evaluation is expected to provide guidance in formulating more optimal input management strategies, as well as increasing the sustainability and productivity of plantations in the future.In the context of managing PKS waste into organic fertilizer, these results provide several important implications. First, the use of organic fertilizer from PKS waste can reduce operational costs associated with the purchase of inorganic fertilizer (Nurnawati et al., 2022). For example, in 2020, operational costs reached IDR 1,311,024,299 with a CRS efficiency of 95.03%. By optimising the use of organic fertilizers, these costs can be further reduced, increasing efficiency (Yani et al., 2022).

Second, the labour used for the process of managing PKS waste into organic fertilizer can be allocated more effectively. In 2023, labour costs reached IDR 6,362,797,764 with a CRS efficiency of 82.97%. Optimising the process of converting waste into organic fertilizer can increase labour efficiency, reduce labour costs, and increase productivity (Ratriyanto et al., 2019).

Third, the amount of production and production income shows that the use of organic fertilizer can increase output and income. For example, in 2022, the total production reached 6,005,961 with a revenue of IDR 16,372,857,704, although the CRS efficiency was only 52.09%. By increasing the efficiency of organic fertilizer use, production

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and income can be increased further (Salam et al., 2021).

The practical implication of this finding is that plantation managers need to focus on improving scale efficiency, especially in years with low scale efficiency values. This could involve further analyses of factors affecting production scale and adjustments to management strategies. Improving technical efficiency under CRS conditions can be achieved by identifying and reducing sources of inefficiency that may be related to sub-optimal input management. By understanding these efficiency outcomes, plantation managers can take strategic steps to improve the productivity and sustainability of oil palm plantations, particularly in utilising pks waste as organic fertilizer. This is expected to make a significant contribution to the literature on sustainable management of oil palm plantations and offer practical solutions for improving efficiency and sustainability in plantation management practices.

Land Area to Efficiency

Land area is one of the main variables that affect productivity and efficiency. In general, the larger the land area under management, the greater the production potential that can be achieved (Safitri et al., 2020). However, the main challenge that arises is how to optimise land use to remain efficient and sustainable (**Figure 1**). Land efficiency is not only measured by the quantity of production, but also by how the land is managed by considering ecological aspects, such as the maintenance of soil fertility and conservation of natural resources. Inefficient land management often leads to land degradation, which in turn reduces productivity and potentially damages ecosystems.

The utilisation of waste from Palm Oil Mills (PKS) into organic fertilizer is one of the innovative approaches in supporting the sustainability of oil palm plantation management (Azman et al., 2023). Palm oil mill waste, which includes empty bunches, shells, and fibre, is often considered a worthless by-product. However, when processed into organic fertilizers, these wastes not only help in reducing dependence on inorganic fertilizers, but also contribute to improved soil fertility (Rai et al., 2024). The use of organic fertilizer from PKS waste can increase soil water retention capacity, improve soil structure, as well as provide more sustainable nutrients for oil palm plants (Awoh et al., 2023).

Efficiency in oil palm plantation management depends not only on the scale of land area under management, but also on how other resources, such as labour and operational costs, are optimally used (M. Musa et al. 2021; Akolgo et al. 2023). The use of efficiency analysis models, such as Data Envelopment Analysis (DEA), can provide an overview of how effectively each plantation unit utilises available inputs to produce maximum output. In some cases, plantations with larger land areas are not necessarily more efficient if their management does not take into account the optimisation of resources and technology used.

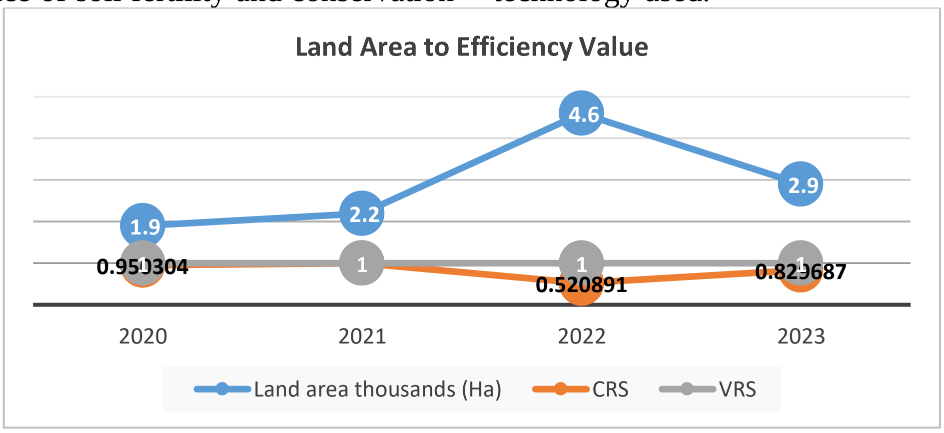

Figure 1. Land area to efficiency (Source: Data Processed with STATA 13)

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A sustainable oil palm plantation management system requires integrating economic, environmental and social aspects (Pinca et al., 2024). From an economic perspective, sustainability must be realised through increased productivity and cost efficiency (Yu et al., 2024). The use of PKS waste as organic fertilizer can reduce the cost of purchasing chemical fertilizers, while maintaining soil fertility (Han et al., 2021). From an environmental perspective, sustainable management aims to minimise negative impacts on ecosystems, including mitigation of greenhouse gas emissions and conservation of biodiversity (Bhatia et al., 2023).

Implementing a sustainable management system that utilises PKS waste as organic fertilizer also has a positive social impact. By reducing the use of chemical fertilizers, the health of communities around plantations can be better maintained, as the risk of environmental and groundwater pollution associated with the use of hazardous chemicals can be minimised (Andrade et al., 2022). In addition, community involvement in waste management and the application of organic technologies can increase social acceptance and support social stability around plantations (Rasul & Thapa, 2004).

Overall, the combination of efficient land area management, utilisation of PKS waste as organic fertilizer, and implementation of sustainable management systems are strategic steps that can improve the competitiveness of the palm oil industry at the global level (Hawanda & Sudiarti, 2023). This approach not only ensures the sustainability of production, but also provides long-term benefits to the environment and society. Therefore, the integration of these factors should be a key focus in the development of future policies and management practices for oil palm plantations.

Operating Cost to Efficiency

Operational costs play an important role in determining the efficiency of oil palm plantation management, especially in the context of utilisation of palm oil mill (PKS) waste into organic fertilizer (Dahliani et al., 2022). Efficiency here refers to the plantation's ability to maximise output in the form of both production and income with minimal inputs (**Figure 2**). In sustainable oil palm plantation management, the utilisation of PKS waste for organic fertilizer production not only reduces operational costs but also contributes to improving soil fertility and reducing dependence on chemical fertilizers (Rai et al., 2024). In oil palm plantations, operational costs generally include costs for fertilizer, labour, and infrastructure maintenance. The traditional use of inorganic fertilizers entails significant costs, which in turn affects total operational costs (García Castellanos et al., 2023). However, by processing PKS waste into organic fertilizer, plantations can reduce the expenditure associated with purchasing chemical fertilizers. This not only improves cost efficiency, but also provides environmental benefits by reducing the carbon footprint and managing waste more sustainably (Holka et al., 2022).

Higher operational efficiency can be achieved through careful management, where PKS waste is converted into organic fertilizer that is directly used to increase land productivity (Ilahi, 2021). The use of organic fertilizer from palm oil waste is given consistently every three months with the right dosage to ensure the availability of nutrients for oil palm (Harefa, 2022). This allows plantation managers to reduce the use of chemical fertilizers, which are not only expensive but also contribute to land degradation in the long run. Thus, the utilisation of PKS waste into organic fertilizer not only helps in managing operational costs but also encourages more environmentally friendly practices.

Sustainable oil palm plantation management demands a holistic approach, where operational efficiency is combined with strategies that prioritise environmental sustainability. This includes the integration of PKS waste treatment technology to produce

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organic fertilizer, which not only reduces costs but also improves soil quality. As such, this approach can be seen as a long-term investment that supports the sustainability of the plantation system.

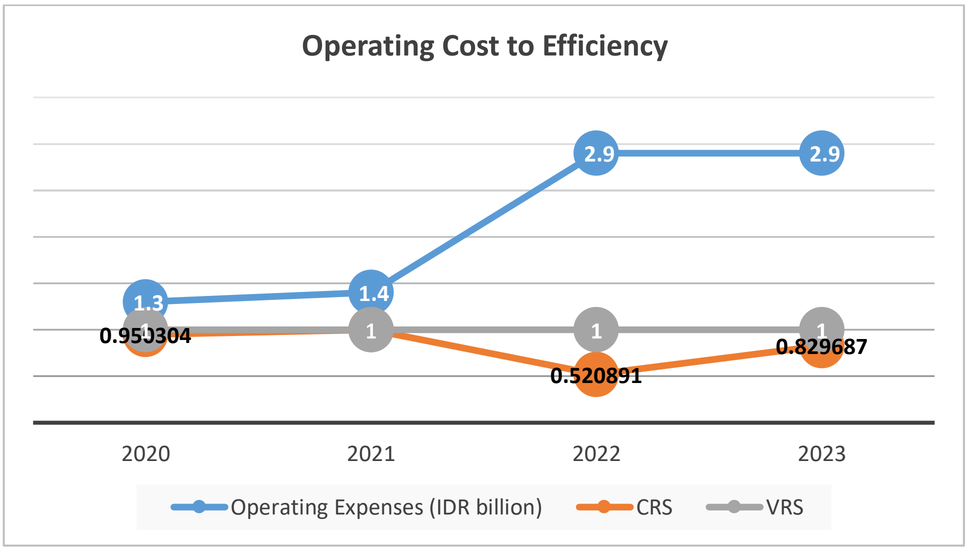

Figure 2. Operating cost to efficiency (Source: Data Processed with STATA 13)

In addition, the utilization of PKS waste as an organic fertilizer has also contributed to increased production yields at the Padasa Enam Utama oil palm plantation (He et al., 2024). More fertile and healthy soil as a result of using organic fertilizer tends to produce more productive oil palm plants, which in turn increases plantation income. The use of organic fertilizer from PKS waste can be considered an efficient and sustainable management strategy in oil palm plantations. In the long term, an efficient and sustainable oil palm plantation management system, utilizing PKS waste, can provide significant economic and environmental benefits.

By reducing operational costs and improving production efficiency, oil palm plantations can become more competitive while supporting global efforts to reduce the industry's negative environmental impacts. Therefore, oil palm plantation management that integrates cost efficiency and environmental sustainability through the utilisation of PKS waste into organic fertilizer should be viewed as a key strategy in achieving sustainability in oil palm plantation management (Abogunrin-Olafisoye et al., 2024).

Labour Cost to Efficiency

Sustainable palm oil management requires a holistic approach that includes economic, environmental and social aspects. One important factor in oil palm management is labor cost, which significantly determines operational efficiency. This study aims to analyze the impact of labor costs on the efficiency of oil palm management with a focus on utilizing PKS (Palm Oil Mill) waste as organic fertilizer, based on data from 2020 to 2023. In 2020, labor costs were recorded at IDR 2.850 billion with a land area of 1,923 hectares and production of 4,787,370 kg, generating revenue of IDR 10.116 billion (**Figure 3**).

The technical efficiency score (CRS) is 0.95, indicating that the efficiency in input use is relatively high. However, this value indicates that there is potential for improvement, especially in terms of managing labor costs that can affect production yields. In 2021, there was an increase in land area to 2.153 hectares and labor costs increased to IDR 2.852 billion, with technical efficiency reaching a maximum value of 1, indicating full efficiency. This reflects that higher investment in labor can increase efficiency, especially if it is well managed.

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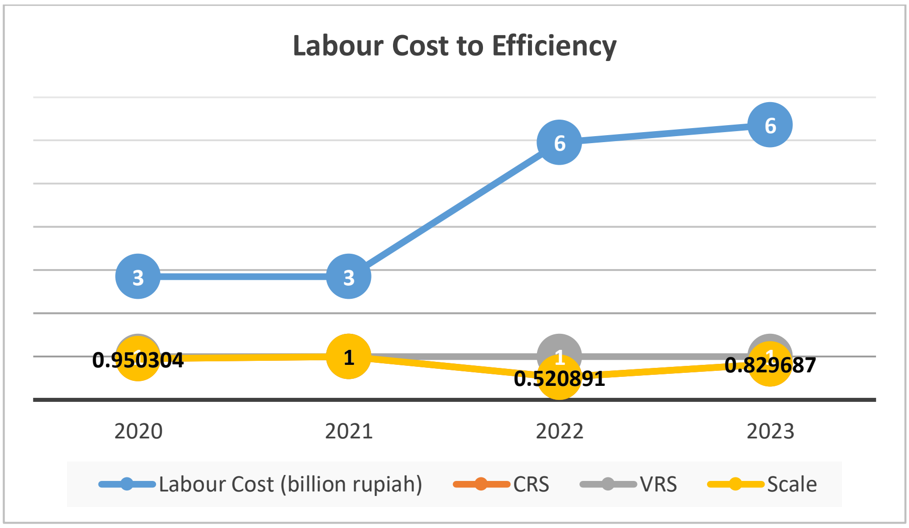

Figure 3. Labour cost to efficiency (Source: Data Processed with STATA 13)

However, the situation changed in 2022 and 2023. In 2022, although the land area increased significantly to 4,568 hectares and production increased to 6,005,961 kg, labor costs also increased to IDR 5.964 billion. Despite the increase in production, the CRS value decreased to 0.52, indicating low technical efficiency. This decline can be attributed to inefficiencies in the management of labor costs, which may be due to suboptimal operational processes or increased costs that are not matched by increased production output. In 2023, the land area shrinks again to 2,924 hectares with labor costs of IDR 6.362 billion, where technical efficiency is recorded at 0.83. This shows a decrease in efficiency despite the decrease in land area and increase in labor costs.

The utilization of PKS waste as organic fertilizer can have a significant impact on the efficiency of oil palm management. PKS waste is one of the by-products of the palm oil processing process that is often considered as an environmental burden. However, if managed and utilized properly, this waste can be converted into organic fertilizer which is useful for improving soil fertility and reducing the need for external chemical fertilizers. The process of converting PKS waste into organic fertilizer requires efficient labor and technology. Therefore, high labor costs can have implications for suboptimal waste management if not matched with appropriate technology.

From a sustainability perspective, utilizing PKS waste for organic fertilizer can reduce environmental impacts and improve long-term economic efficiency. The utilization of PKS waste as organic fertilizer presents significant environmental and economic benefits in enhancing the sustainability of oil palm plantations. From an environmental perspective, PKS waste used as organic fertilizer helps to reduce dependency on chemical fertilizers, which have been known to adversely affect soil health, greenhouse gas emissions, and water quality. This waste also contributes to soil improvement by adding organic matter, enhancing water retention, and improving soil structure (Azman et al., 2023; Han et al., 2021). Consequently, the application of organic fertilizer derived from PKS waste leads to better soil fertility, reduced environmental pollution, and supports environmentally friendly agricultural practices.

Economically, the use of PKS waste as organic fertilizer lowers operational costs related to chemical fertilizer purchases, thereby enhancing efficiency and profitability (Kurniawan et al., 2022; Yani et al., 2022). This is especially important for long-term sustainability, particularly for smallholder farmers who are vulnerable to the

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fluctuating prices of chemical fertilizers. Utilizing PKS waste not only provides economic benefits but also promotes social sustainability by improving labor efficiency in waste management and empowering local communities through composting activities ((Ratriyanto et al., 2019; Mulyasari et al., 2023). Overall, this strategy shows significant potential for improving the economic resilience of palm oil plantations while providing positive environmental impacts.

However, the effectiveness of this waste utilization is highly dependent on the application of appropriate technology and adequate manpower training. Without appropriate technology, labor costs for waste management may increase without providing optimal results, which in turn may affect overall technical efficiency. To achieve better efficiency in oil palm management, it is important to adopt an integrated approach. This includes efficient management of labor costs, application of appropriate technology for mill waste utilization, and adequate training for the workforce. Further research is needed to evaluate in detail the relationship between labor costs, waste utilization technology, and technical efficiency in oil palm management. With this approach, companies can improve operational efficiency and support sustainable and environmentally friendly palm oil management practices.

CONCLUSION

This reseacrh underscores the environmental and economic advantages of utilizing Palm Oil Mill Solid (PKS) waste as organic fertilizer, demonstrating a viable path toward sustainable management in oil palm plantations. The findings reveal that PKS-derived fertilizers can significantly reduce dependency on chemical fertilizers, improve soil health, and lower operational costs, thereby enhancing both environmental and economic sustainability. The study's use of Data Envelopment Analysis (DEA) has been pivotal in highlighting efficiency improvements across plantation management. By identifying optimal input-output relationships, DEA offers a quantifiable basis for sustainable practices that minimize waste, optimize resources, and maintain productivity.

The main contribution of this research lies in its empirical evidence supporting the environmental and economic feasibility of PKS waste as a resource, which not only contributes to reducing the industry's carbon footprint but also strengthens economic resilience in the face of fluctuating fertilizer costs. This work enriches the existing body of literature by demonstrating that organic waste from oil palm processing, often considered a disposal burden, can be recontextualized into a valuable input for sustainable agricultural practices. Further research could explore the long-term soil health impacts of PKS-based fertilizers on different soil types and analyze economic outcomes across various scales of plantation operations. Expanding on DEA application, future studies might also investigate efficiency metrics that consider broader environmental and social variables, thereby deepening our understanding of sustainable agricultural practices within the palm oil sector. This study highlights that integrating PKS waste management into plantation operations is a strategic step toward aligning with global sustainability goals and ensuring a balanced, resilient approach to palm oil production.

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