ISSN 2599-3496 print
ISSN 2614-2376 online
Volume 9, Number 1, 2026

INTERNATIONAL JOURNAL of OIL PALM

By Indonesian Oil Palm Society

BPDP MAKSI

INTERNATIONAL JOURNAL of OIL PALM

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PUBLISHER
Indonesian Oil Palm Society
International Journal of Oil Palm

INTERNATIONAL JOURNAL of OIL PALM

ISSN: 2599-3496 print
ISSN: 2614-2376 online

Volume 9, Number 1, 2026
Page: 1–7
DOI: 10.35876/ijop.v9i1.137

Generative AI-based Decision Support System for Detecting Palm Fruit Quality

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ABSTRACT

Indonesia's dominance as a global palm oil producer is challenged by the economic precarity of its 6.9 million smallholder farmers,dual threat to their sovereignty. The first is a structural asymmetry of information and weak bargaining power, making them vulnerable to subjective assessments of Fresh Fruit Bunch (FFB) quality, leading to unilateral price cuts and significant income losses. The second is mounting global market pressure to comply with sustainability standards (ISPO/RSPO), which act as non-tariff barriers through complex traceability and documented quality controls that are difficult for smallholders to meet. To address these challenges, this study designed and evaluated a generative AI-based Decision Support System (DSS) to provide objective analysis and strengthen farmers' decision-making capabilities. The methodology involved using few-shot prompting on the Gemini AI platform, with the system's performance then tested through a controlled technology intervention involving 20 smallholder farmers in South Lampung, a region with a high incidence of price disputes. Key findings indicate that the DSS, through real-time image analysis, can classify FFB maturity with a quantitative accuracy of 80%. Its implementation in the field consistently resulted in a 45% reduction in price disputes and an average increase in selling prices of 9-13%, as farmers utilized validation data from the system during negotiations. The technology achieved a high adoption rate of 80%, driven by increased farmer confidence and direct positive impacts on their income. In conclusion, this DSS has proven not only a valid technical tool but a crucial catalyst for economic empowerment, effectively bridging the information gap and empowering farmers for integration into a more equitable and sustainable global supply chain. Further research is recommended to test the system's scalability and generalization across larger populations in regions like North Sumatra or Kalimantan to validate its efficacy amidst diverse agronomic and socio-economic characteristics.

Keywords: Decision Support System, Economic Empowerment, Generative AI, Information Asymmetry, Technology Adoption

INTRODUCTION

Indonesia is a global leader in palm oil production, a strategic commodity that is the backbone of the national economy and a source of livelihood for millions of its people. This sector is unique in that around 40% of total national production is contributed by approximately 6.9 million smallholders, making them a critical

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component in the domestic and global supply chain (Hidayat *et al.* 2021). Despite their central role, these farmers consistently face structural and economic vulnerabilities. One of the main challenges is the asymmetry of information in the assessment of Fresh Fruit Bunch (FFB) quality. Without objective assessment tools, farmers often find themselves in a weak bargaining position, vulnerable to subjective assessments by buyers that can lead to arbitrary price reductions and significant income losses (Sihombing & Tandra 2019).

This situation is particularly pronounced in major production centers, one of which is Lampung. As one of the nation's palm oil hubs, smallholder farmers in Lampung are the driving force behind the regional industry. However, they face the same challenges: uncertainty in harvest quality assessment and pressure to comply with global sustainability standards such as the Indonesian Sustainable Palm Oil (ISPO) and Roundtable on Sustainable Palm Oil (RSPO). The complexity and cost of certification often act as barriers, further marginalizing smallholder farmers who lack resources (Brandi *et al.* 2015; Sinaga *et al.* 2024). To understand and address these challenges directly at the grassroots level, this study focuses its interventions on farming communities in South Lampung District. In response to these challenges, various technological interventions have been explored. Decision Support Systems (DSS), integrated with artificial intelligence (AI) such as computer vision, show great potential for objectifying the process of assessing agricultural product quality (Kurniawan *et al.* 2023; Tjahjadi *et al.* 2024). However, conventional AI models like Convolutional Neural Networks (CNN) typically require very large labeled datasets for training. This requirement poses a major challenge in agricultural environments like South Lampung, where collecting large-scale data is often impractical and costly (Rupanagudi *et al.* 2023).

This study introduces a new approach to bridge this gap by designing and evaluating a Generative AI-based DSS. Its key innovation lies in the application of few-shot prompting methodology, enabling the system to classify TBS maturity with high accuracy using only a few training images. Unlike data-intensive models, this approach offers a more practical, affordable, and scalable solution. By placing this technology directly in the hands of farmers, the system not only functions as a technical tool but also as a strategic catalyst for economic empowerment, aiming to address information asymmetry and strengthen farmers' bargaining positions in South Lampung.

Based on this background, the specific objective of this research is to design and develop an expert system using few-shot prompting on a Generative AI platform to classify TBS maturity based on real-time image analysis.

MATERIALS AND METHODS

Research Design

This study uses a quasi-experimental design with a technological intervention approach. This design involves measuring key variables before (pre-test) and after (post-test) the implementation of a Decision Support System (DSS) based on Generative Artificial Intelligence (Generative AI). This approach was chosen to evaluate the causal impact of the technology intervention on the accuracy of Fresh Fruit (FFB) classification, price disputes, and farmer income within the same group of participants.

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Location and Sample Selection

Field research was conducted in South Lampung Regency, Lampung Province, Indonesia. This location was strategically chosen because it is one of the centers of small-scale oil palm plantations with a high level of price disputes due to subjective assessments of the quality of Fresh Fruit Bunches (FFB).

The research sample consisted of 20 small-scale oil palm farmers (N=20) selected using purposive sampling techniques. The inclusion criteria for participants were: (1) being an independent farmer who actively sells FFB; (2) having a written history or personal report of frequent price disputes; and (3) being willing to participate in the entire research process, from initial data collection to the use of the application.

Materials

Hardware: Image data collection in the field is carried out using a mid-range smartphone commonly used by farmers, namely the Poco X7, which is equipped with a 50-megapixel main camera. This device was chosen to ensure that the system can operate on affordable and widely used hardware. Software: A native mobile application for the Android operating system was developed as the user interface (DSS). The application is designed with a simple workflow, allowing users to select and upload existing FFB images from their device gallery, then send them to the Google Application Programming Interface (API) endpoint for analysis. AI Model: The core component for image analysis is the multimodal large language model Gemini Pro (LLM). This model was developed by Google and is accessed through their official API. It was chosen for its advanced ability to understand and analyze the visual context of images accompanied by text-based instructions (prompts).

Research Procedures

The workflow in picture 1 begins when the user accesses the system. The first step is to enter multimodal input, where the user uploads an image of Fresh Fruit Bunches (FFB) and accompanies it with a prompt or text command. This combined input is then processed by a Large Language Model (LLM), which analyzes the image in the context of the instructions provided.

Once the analysis is complete, the system provides a response via the chatbot interface. This response includes the TBS ripeness classification results along with other relevant details. The final stage is user evaluation, which involves a conditional branch:

• If the user finds the response satisfactory (Yes), the workflow is considered complete.

• However, if the response is deemed unsatisfactory (No), the system will direct the user back to the initial stage to re-enter the image and prompt, allowing the analysis process to be repeated until a satisfactory result is obtained.

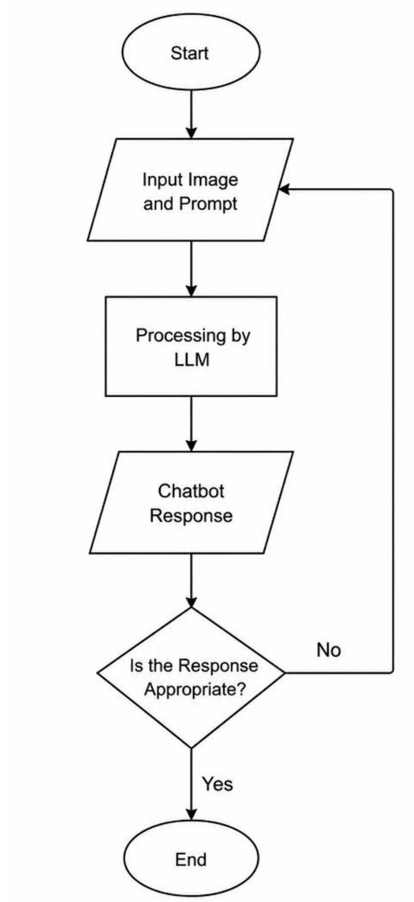

Figure 1 System Development Procedure

AI Implementation: Few-Shot Prompting

The implementation of AI does not involve training the model from scratch. Instead, the few-shot prompting method is used to guide the Gemini Pro model. A structured multimodal prompt is designed, consisting of three main components:

1. Instructions (Role and Tasks): Clear text commands that direct the AI to act as an expert FFB assessor. Example: “You are an expert in classifying Fresh Fruit Bunches (FFB) of oil palm. Based on the provided images, classify the FFB into one of three categories: ‘UNRIPE’, ‘RIPE’, or ‘OVERRIPE’.”

2. Examples (Shots): Several example images with correct classification labels for each category are included in the prompt to ‘teach’ the model. Example: [unripe_

ffb_image_1.jpg] -> UNRIPE, [ripe_ffb_image_1.jpg] -> RIPE, [overripe_ffb_image_1.jpg] -> OVERRIPE. Three to five examples for each category are used to build an effective prompt.

3. The Actual Question: New FFB images taken by farmers from the app are then attached at the end of the prompt as a question to be answered by the AI.

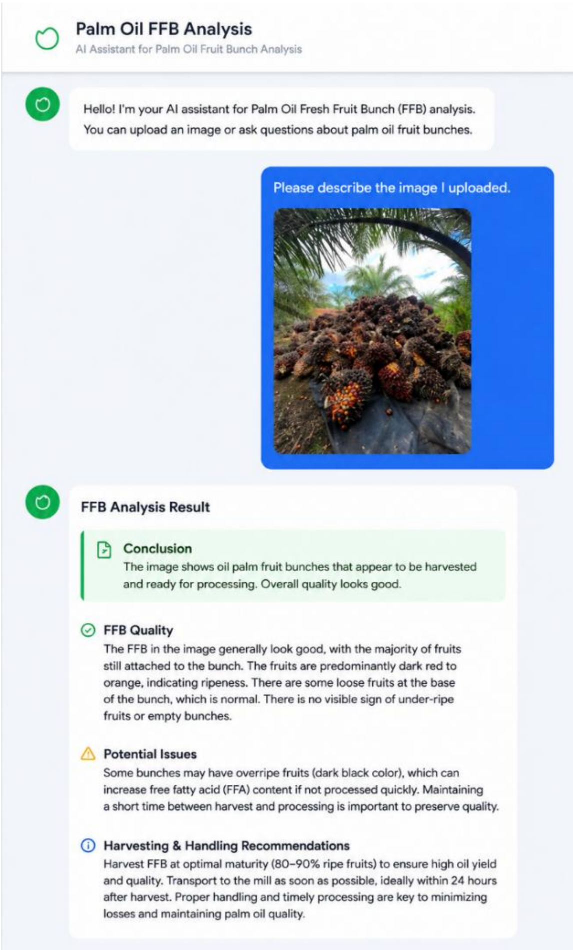

Figure 1 Prompt AI Analysis

Field Intervention Procedure

The field intervention procedure will be carried out from September 2024 to March 2025 and will be divided into four stages:

a. Initial Data Collection: During the first two months (January-February 2025), initial data will be collected from 20 farmers regarding the average selling price per kilogram and the frequency of price disputes they experience.

b. Training and Application Distribution: In early March 2025, a workshop session was held to train farmers in the use of the application. The training specifically covered the first steps of photographing FFB, then opening the DSS application to select and upload images from the gallery to obtain classification results.

c. Application Usage Period: From April 2025 to May 2025, farmers actively used the DSS application during FFB sales transactions. They were instructed to use the classification results from the application as an objective validation tool and negotiation support with buyers.

d. Final Data Collection: In June 2025, data on average selling prices and dispute frequencies were collected again. Additionally, post-intervention question-naires were distributed to measure the level of acceptance and adoption of the technology.

RESULTS AND DISCUSSION

Result System Classification Performance

The decision support system (DSS) based on generative artificial intelligence (AI) showed high performance in classifying the maturity level of fresh fruit bunches (FFB) in field test conditions. This system achieved 80% quantitative classification accuracy in identifying the correct maturity categories (unripe, ripe, and overripe), as shown in the table below.

Discussion

The results of this study indicate that a Decision Support System (DSS) supported by generative artificial intelligence can serve as a valid technical tool and an important catalyst for economic empowerment among small-scale oil palm farmers. A classification accuracy of 80% is a strong finding, demonstrating that the few-shot prompting approach with the Gemini Pro model is highly effective for this specific visual assessment task. This accuracy rate is comparable to that reported in studies using conventional data-intensive Convolutional Neural Network (CNN) models for fruit assessment (Kurniawan *et al.* 2023; Tjahjadi *et al.* 2024). However, the uniqueness and main advantage of our system lies in its implementation method. By eliminating the need for large, curated training datasets—a significant barrier highlighted by Rupanagudi *et al*. (2023)—the generative AI approach offers a more flexible, scalable, and cost-efficient solution for implementation in resource-constrained agricultural environments.

Table 1. Comparison Between Actual FFB Ripeness Condition and System Classification Results

No.	Farmer ID	Actual Condition	System Result	Test Result
1	P001	Ripe	Ripe	Correct
2	P002	Ripe	Ripe	Correct
3	P003	Unripe	Unripe	Correct
4	P004	Ripe	Overripe	Incorrect
5	P005	Overripe	Overripe	Correct
6	P006	Ripe	Ripe	Correct
7	P007	Unripe	Unripe	Correct
8	P008	Ripe	Ripe	Correct
9	P009	Unripe	Ripe	Incorrect
10	P010	Ripe	Ripe	Correct
11	P011	Overripe	Overripe	Correct
12	P012	Ripe	Ripe	Correct
13	P013	Unripe	Unripe	Correct
14	P014	Ripe	Ripe	Correct
15	P015	Overripe	Ripe	Incorrect
16	P016	Ripe	Ripe	Correct
17	P017	Unripe	Unripe	Correct
18	P018	Ripe	Unripe	Incorrect
19	P019	Overripe	Overripe	Correct
20	P020	Ripe	Ripe	Correct

*Notes:
Test Results Summary:
Total Tests: 20
Number of Correct Answers: 16
Number of Incorrect Answers: 4
Accuracy Rate: (16÷20) * 100% = 80%

The most significant implication of this research is its measurable socio-economic impact. By providing farmers with objective and easily understandable evidence regarding the quality of their harvests, the DSS effectively strengthens their bargaining power. This shifts the dynamics of price negotiations from being based on subjective assessments and power imbalances to being data-driven, thereby reinforcing the argument that technological tools can help smallholder farmers overcome non-tariff barriers and achieve fairer market integration (Brandi *et al.* 2015; Sinaga *et al.* 2024).

Additionally, the high adoption rate of 80% indicates that the technology is not only effective but also aligned with the needs and capabilities of end-users. This finding aligns with existing DSS literature, which states that user acceptance is highly influenced by perceived usefulness and ease of use

(Chen *et al.* 2024). The direct and immediate positive impact on farmers' income likely creates a strong positive feedback loop, encouraging continued use. The reported increase in farmers' confidence is a critical finding, albeit qualitative. This suggests that the value of DSS extends beyond mere data provision; it functions as an empowerment tool that enhances farmers' role in economic transactions. While these findings are promising, the study's scope is limited by sample size (n=20) and a single geographic location. Future research should aim to validate these findings in larger and more diverse populations of farmers across regions to assess the generalizability and scalability of the system.

Findings

The main findings of this study indicate that a generative AI-based Decision Support System (DSS) serves as an effective solution to the problem of information asymmetry faced by oil palm farmers. Technically, this system has been proven valid with its ability to classify the maturity of Fresh Fruit Bunches (FFB) with a quantitative accuracy of 80%. The implementation of this tool directly addresses issues at the transaction level, as evidenced by a significant 45% reduction in price disputes. Technology adoption among end-users is also very high, with an adoption rate of 80%, driven by increased farmer confidence. Collectively, these findings confirm that the DSS functions as a strategic tool that bridges information gaps and effectively strengthens farmers' bargaining positions within the supply chain.

CONCLUSION

Based on the research results, it can be concluded that the Decision Support System (DSS) based on Generative Artificial Intelligence (Generative AI) has been designed, implemented, and evaluated effectively. This system has proven capable of classifying the maturity level of Fresh Fruit Bunches (FFB) with high quantitative accuracy of 80%. Therefore, this research makes a significant contribution by demonstrating that accessible Generative AI technology, such as through few-shot prompting, is not only a valid technical tool but also an effective strategic instrument for bridging information gaps, strengthening bargaining positions, and ultimately enhancing farmers' economic sovereignty within the palm oil supply chain.

Suggestions for future researchers

Based on the findings and limitations of the current study, future research should focus on validating the scalability and generalization of the system by testing it on larger populations of farmers in various regions such as North Sumatra or Kalimantan. In addition, the model's analytical capabilities can be expanded beyond maturity classification to include disease detection or weight estimation. Longitudinal studies are also needed to measure the long-term economic impact more comprehensively. From a technological perspective, the development of an on-device version that does not depend on internet connectivity, as well as integration with supply chain platforms and sustainability certification (ISPO/RSPO), will be the next strategic steps to increase the adoption and impact of the system more broadly.

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INTERNATIONAL JOURNAL of OIL PALM

ISSN: 2599-3496 print
ISSN: 2614-2376 online

Volume 9, Number 1, 2026
Page 8–19
DOI: 10.35876/ijop.v9i1.158

Metamorphosis of Palm Oil Settlement in Forest Areas: Policy Trajectories after Government Regulation Number 45 of 2025

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ABSTRACT

Palm oil is a strategic commodity that supports Indonesia’s economy. One of the problems in palm oil governance is the overlap between forest areas and palm oil plantations. This problem has caused Indonesian palm oil to receive a negative response in the international market, prompting the government to formulate a resolution policy since 2010. On September 19, 2025, the government released the latest policy through Government Regulation Number 45 of 2025 on Amendments to Government Regulation Number 24 of 2021 on Procedures for Imposing Administrative Sanctions and Procedures for Non-Tax State Revenue from from Administrative Fines in the Forestry Sector. This policy has caused concern because it deemed detrimental to palm oil industry. The study applies a normative juridical method and attempts to analyze the new contents of Government Regulation Number 45 of 2025 to identify policy recency. The study identifies four substantial provisions in Government Regulation Number 45 of 2025, namely the strengthening of Forest Area Control Task Force; revision of the formula for calculating administrative fines; “repossession” of forest areas; and the removal of the legality of continuing operations in Article 110B scheme. There are three crucial issues that have the potential to cause legal uncertainty, namely the lack of clarity on follow-up actions after “repossession” in conservation and protected forests; the weak principle of enforceability of administrative sanction decisions; and the lack of clarity on the agency that manages non-tax state revenue from administrative fines. The study recommends the government to intensify “repossession” in conservation and protected forests and restore the ecosystems; establish a system for delivering administrative sanction decisions that can be immediately accepted by legal subjects; and appoint an agency to manage non-tax state revenue from administrative fines.

Keywords: administrative fines, forest area, palm oil, repossession.

INTRODUCTION

Indonesia is the world's largest palm oil producer, with 16.83 million hectares and 46.82 million tons production in 2022. Indonesia is also the world's largest exporter of crude palm oil (CPO), accounting for more than 55% of total world exports (Ministry of Agriculture 2024). In 2023, the palm oil industry's contribution to the state budget reached IDR 88 trillion, consisting of IDR 50.2

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trillion in tax revenue, IDR32.4 trillion in non-tax state revenue, and IDR6.1 trillion in export duties (Saptati 2024).

One of the problems in palm oil governance is the overlap between forest areas and palm oil plantations. There are two typologies of this phenomenon. First, there are palm oil plantations operating in areas that have long been designated as forest areas. Second, palm oil plantations were established before the forest area was designated (Supriyono 2024). National Reconciliation of Palm Oil Data 2019 from the Ministry of Agriculture indicates that there are 3.372.615 hectares of palm oil plantations in forest areas (Violetta 2021). The government also identify 4,2 million hectares illegal mining operations in forest areas (Naibaho 2025).

Palm oil legality is a hot topic in the international market. Non-tariff barriers exist, most of which involve the issuance and enforcement of regulations in export destination countries, which tend to be discriminatory, and some involve negative campaigns. Indonesian government strives for international recognition of Indonesia Sustainable Palm Oil/ISPO (Sulaiman *et al.* 2024).

To formulate the resolution to guarantee legal legitimacy, the government has issued policies, starting with Government Regulation Number 10 of 2010 on Procedures for Changing the Designation and Function of Forest Areas (GR 10/2010), GR Number 60 of 2012 on Amendments to GR 10/2010 (GR 60/2012), GR Number 104 of 2015 on Procedures for Changing the Designation and Function of Forest Areas (GR 104/2015), Law Number 11 of 2020 on Job Creation (Law 11/2020) in conjunction with GG Number 24 of 2021 (GR 24/2021) jo. Law Number 6 of 2023 (Job Creation Law), and all these policies were finally metamorphosed into GR Number 45 of 2025 on Amendments to GR 24/2021 (GR 45/2025). GR 24/2021 is the implementing regulation of Articles 110A and 110B of Law Number 18 of 2013 on the Prevention and Eradication of Forest Destruction (Anti-Forest Destruction Law) jo. Job Creation Law. The policy is expected to resolve all developed activities in forest areas without forestry permits (developed activities), but the Ombudsman's report shows the implementation of GR 24/2021 has been slow because 93.84 percent of legal subjects have not yet been processed (Ombudsman 2024).

The government then passed GR 45/2025 as a "panacea policy" which expected to correct previous policies. However, this GR immediately caused concern among palm oil industry. This regulation is considered to increase the burden due to heavy fines, potentially crippling the palm oil sector, especially for farmers and medium-sized businesses, and disrupting legal certainty and investment climate (Manurung 2025). It is important to examine GR 45/2025 to identify policy breakthroughs in strengthening palm oil and natural resource governance. This study aims to compare GR 45/2025 with GR 24/2021 to analyze the latest policy offered. Thus, the question in this study is how the policy on settlement of plantation, mining, and other activities in forest area will be implemented after the issuance of GR 45/2025.

MATERIALS AND METHODS

This study is normative-juridical, namely legal research that examines aspects of positive law. The study analyses laws and regulations relevant to the problem under study, namely GR 45/2025 and other relevant regulations. The focus of this study is norm system. The technique used in data analysis is content analysis, a method for understanding the content of text. Content analysis is used to analyse regulations, contracts, court verdict, and policy.

RESULTS AND DISCUSSION

There are three categories of forest areas in Indonesia: conservation forests, protected forests, and production forests. Based on GR Number 23 of 2021 on Forestry Implementation (GR 23/2021), conservation forests have the primary function of preserving plant and animal diversity and their ecosystems; protected forests have the primary function of protecting life support systems to regulate water management, prevent flooding, control erosion, prevent seawater intrusion, and maintain soil fertility; and production forests have the primary function of producing forest products. Production forests were previously divided into three categories: limited production forests, permanent production forests, and convertible production forests. With the issuance of GR 23/2021, production forests are now divided into two categories: permanent production forests and convertible production forests. The settlement of activities in forest areas is a complex issue for which policy solutions continue to be sought. The government has issued various legal/policy products.

Table 1 Sequence of Policies for Developed Activities Settlement in Forest Areas

No.	Policy Products	Explanation
1.	GR 10/2010	The release of forest areas for plantation, and businesses must submit replacement land maximum 12 months.
2.	GR 60/2012	Settlement of palm oil plantations maximum six months: in convertible production forest: given release; in limited production forests or permanent production forests: forest area exchange scheme.
3.	GR 104/2015	The settlement of palm oil plantations maximum one year: in convertible production forest: given release; in limited production forests or permanent production forests: forest area exchange scheme; in conservation/protected forest: permit to continue business.
4.	Job Creation Law jo. GR 24/2021	Article 110A applies to palm oil plantations which have location permit/plantation business permit (including a cultivation registration certificate) and align with the spatial plan issued by the authority at the time the business was first established and/or operated; Article 110B applies to plantations, mining, and other activities, subject to administrative fines.
5.	GR 45/2025 jo. Presidential Regulation Number 5 of 2025 on Forest Area Order (PR 5/2025)	Establishing Forest Area Order Task Force and the “repossession” instrument.

Source: Author's recapitulation.

There Basically, plantation activities are non-forestry activities. Non-forestry development in forest areas is regulated by Article 38 verse (1) of Law Number 41 of 1999 on Forestry (Forestry Law), which reads: “*The use of forest areas for development purposes outside of forestry activities can only be carried out in production forest areas and protected forest areas*.” Regulation of the Minister of Environment and Forestry Number 7 of 2021 on Forestry Planning, Changes in the Designation and Function of Forest Areas, and the Use of Forest Areas (MR 7/2021), which is a derivative of Forestry Law and GR 23/2021, regulates the use of forest areas for plantation activities. Article 274 of MR 7/2021 stipulates that: "*Development interests outside of forestry activities as referred to in Article 273 verse (1) include supporting facilities, namely: ... s. plantations.*"

Regarding palm oil plantation in forest areas, it is necessary to distinguish between normal schemes and developed activities schemes. Palm oil plantations in forest areas under normal schemes can be performed with release approval. Releases can only be granted in convertible production forest.

Activities carried out prior to November 2, 2020 (the enactment date of Law 11/2020) shall be completed in accordance with the principle of *ultimum remedium* as stipulated in Articles 110A and 110B. Article 110A is specifically intended for palm oil plantation and sets a three-year deadline for processing, namely until November 2, 2023, and requires the payment of forest resource provisions and reforestation funds.

Meanwhile, Article 110B applies to plantation, mining, and other activities involving oil and gas, geothermal energy, fish farming, agriculture, settlements, nature tourism, industry, and/or facilities and infrastructure. The following administrative sanctions shall be imposed: temporary suspension of business activities; administrative fines; and/or government coercion. Thus, palm oil plantation that do not have location permits and/or plantation business license and do not align with spatial plans are resolved under the provisions of Article 110B. It should also be emphasized that all activities in forest areas without forestry permits after November 2, 2020, constitute criminal offenses and are subject to criminal sanctions. Job Creation Law and GR 24/2021 also regulate the settlement of community activities. Article 41 verse (1) of GR 24/2021 stipulates that: "In the case of business activities within the Forest Area that do not have a forestry permit as referred to in Article 3 verse (3) are carried out by individuals who have resided in and/or around the Forest Area for at least 5 (five) consecutive years with a maximum area of 5 (five) hectares, shall be exempted from Administrative Sanctions and resolved through Forest Area restructuring." This affirmative policy is continued by GR 45/2025.

Community plantations are not subject to administrative sanctions, but are resolved through forest area management, which may take the form of social forestry; agrarian reform; or changes in the designation and function of forest areas. Based on the provisions of Article 41 verse (1) of GR 24/2021, there are three criteria for individuals to obtain a settlement through forest area restructuring, namely: residing in and/or around the forest area; residing in and/or around the forest area for at least five consecutive years; and controlling a maximum five hectares of forest area.

To implement Job Creation Law and GR 24/2021, the Minister of Environment and Forestry has issued a Decree on Data and Information on Developed Activities in Forest Areas without Forestry Permits, from Phase 1 to Phase 24, with 7.818 legal subjects, including corporations, government agencies, community groups, and individuals. Data from the Ministry of Forestry shows that the implementation of GR 24/2021 in 2025 has resulted in forest resource provisions payments Rp330.039.608.031; reforestation funds USD83.391.951; and administrative fines Rp1.133.842.287.704. The policy for resolving developed activities continues to metamorphose. On January 21, 2025, PR 5/2025 was issued to accelerate the resolution of mining, plantation, and/or other activities within forest areas. PR 5/2025 mandates the formation of the Forest Area Order Task Force, consisting of a Steering Committee chaired by Minister of Defense and an Executive Committee chaired by Deputy Attorney General for Specific Crimes of Attorney General's Office. By August 2025, the Task Force has repossessed 3.325.133 hectares of forest area planted with palm oil. The Task Force has also identified 4.265.376 hectares of illegal mining in forest area (Yaputra 2025). On September 19, 2025, GR 45/2025 was issued, transforming GR 24/2021. In general, GR. 45/2025 offers recent policy input, namely in Table 2.

Table 2 Latest Provisions of GR 45/2025

No.	Provisions	Explanation
1.	Strengthening the role of Forest Area Order Task Force	The authority of the Task Force includes: inventorying data and information on developed activities, providing recommendations to the Minister for administrative sanctions, receiving reports of administrative fines payment, providing recommendations for the revocation of business licenses, conducting repossession, and handover repossessed areas to state-owned enterprises (SoEs), requesting the authorities to freeze assets, and requesting the immigration ministry to prevent persons from leaving the country.
2.	Revision of administrative fines formula	In GR 24/2021, administrative fines are calculated based on profits. Currently, the fine rates are set by sectoral ministries/institutions. For example, the fine rate for plantation activities is determined by Ministry of Agriculture, which is IDR25 million per hectare.
3.	Repossession of forest area	Repossession is an action taken by the central government to save and regulate control of forest areas.
4.	The removal of continuing business under the provisions of Article 110B	Although the legal subject has paid the administrative fine, the forest areas are repossessed.

Source: GR 45/2025.

The enactment of GR 45/2025 has changed the stages of resolving developed activities. Settlement is no longer dominated by the Minister (Minister of Forestry) but involves the Task Force. In addition, GR 45/2025 expands the involvement of several ministries/ institutions, The Attorney General's Office plays a role in reviewing fines, collecting administrative fines, seizing assets, and auctioning seized goods through the state auction office. Financial and Development Supervisory Agency is responsible for reviewing fine rates. Regulating Body of SoEs is tasked with appointing SoEs to manage plantation, mining, and/or other activities. Sectoral ministries/agencies are responsible for determining fine rates. The study compares the differences for administering Article 110B and Article 110A between GR 24/2021 and GR 45/2025 as follows in Table 3. For legal subject that have paid forest resource provisions and reforestation funds under Article 110A, the Minister grants permit in the form of release if activities in production forests or approval to continue business and/or cooperation if activities in conservation/protected forest areas. Approval to continue business is valid for one cycle (15 years from the planting period). Meanwhile, cooperation is carried out if palm oil plantation overlaps with forestry permits in production forest areas. The cooperation is carried out for one cycle (maximum 25 years from the period). For the Article 110B scheme, there is a notable change in the process. The outcome is no longer the issuance of legality, but rather a repossession.

Table 3 Comparison of GR 24/2021 and GR 45/2025 (Article 110A)

No	Process	GR 24/2021	GR 45/2025
1.	Inventory of data and information on developed activities	Conducted by the Minister.	Conducted by the Minister and/or Task Force.
2.	Determination of data and information on developed activities	Determined by the Minister.	*Ibid*.
3.	Notification of fulfillment of permit requirements	Conducted by the Minister.	*Ibid*.
4.	Submission of application for completing requirements	Legal subject submits application to the Minister.	*Ibid*.
5.	Application verification	The Minister verifies administrative and technical requirements.	*Ibid*.
6.	Issuance of forest resource provisions and reforestation funds payment order	The Minister issued a letter ordering the payment.	*Ibid*.
7.	Payment of forest resource provisions and reforestation funds	Legal subject reports the payment to the Minister.	*Ibid*.
8.	Issuance of forestry permits	Issued by the Minister.	*Ibid*.
9.	Imposition of administrative sanctions if requirements are not fulfilled within three years	Sanctions may include administrative fines and/or revocation of business licenses determined by the Minister. Payments must be deposited into state treasury within 6 months. Proof of payment shall be reported to the Minister. The revocation of business licenses shall be carried out by the license issuer based on the Minister's recommendation within 30 working days.	Sanctions may take the form of administrative fines and/or other action determined by the Minister based on the recommendations of the Task Force. Payment of administrative fines must be deposited into state treasury within 30 days. Proof of payment shall be reported to the Minister and/or the Task Force. The revocation of business licenses shall be carried out by the issuer based on recommendations from the Minister and/or the Task Force within 10 working days.

Source: GR 24/2021.

The study also identified three crucial issues that require further exploration to obtain legal certainty. The first issue is that GR 45/2025 requires all forest areas that have been repossessed to be released. There are unanswered questions: what if the repossessed forest is conservation or protected forest? Shall those forest area still be released? GR 45/2025 does not provide a policy option that repossession should also be followed by ecosystem restoration, as has been done by the Task Force in Tesso Nilo and Gunung Leuser National Park.

Table 4 Comparison of GR 24/2021 and GR 45/2025 (Article 110B)

No	GR 24/2021		GR 45/2025	
	Process	**Explanation**	**Process**	**Explanation**
1.	Inventory of data and information on developed activities	Conducted by the Minister.	Inventory of data and information on activities carried out	Conducted by the Minister and/or Task Force.
2.	Determination of data and information on developed activities	Determined by the Minister.	Determination of data and information on established activities	*Ibid*.
3.	Data and information verification and validation	Conducted by the Minister based on data and information contained in the Ministerial Decree.	Data and information verification and validation	Conducted by the Minister involving the Task Force based on data and information contained in the Ministerial Decree.
4.	Determination of administrative sanctions	Administrative sanctions in the form of temporary suspension of business, administrative fines, and/or government coercion.	Determination of administrative sanctions	Administrative sanctions include temporary suspension of business, administrative fines, government coercion, and/or repossession.
5.	Enforcement of administrative sanctions	Payments can be made in installments for a maximum 12 months in current fiscal year. The Minister supervises the compliance of administrative sanctions.	Enforcement of administrative sanctions	Payment must be made no later than 30 days after the issuance of the order. If payment is not made, government enforcement may be applied.
6.	Issuance of permits	The Minister grants legality in the form of approval for forest area use, facilitation of cooperation, or orders for the return of areas.	Repossession	Repossession is followed up with forest area release and/or designation of status as state property.
7.	-	-	Business continuation	Assignment of SOEs to manage plantations, mining, and/or other activities.
8.	Government coercion	Applied if the legal subject does not pay administrative fine.	Government coercion	*Ibid*.

Source: GR 24/2021.

GR 45/2025 should differentiate conservation/protected forests and production forests. Conservation/ protected forests must continue to be preserved, and even be expanded. Conservation/protected forests can juridically be released, but their function must first be changed to convertible production forest. If conservation/ protected forests are also released, it will increase ecological disasters, ecosystem fragmentation, biodiversity loss, and exacerbate climate change. Data shows that conservation and protected forests in Indonesia has been decreasing, as outlined in Table 5.

Table 5 Indonesian Forest Area 2017–2024 (Millions of Hectares)

No	Forest Functions	2017	2019	2020	2023
1.	Conservation	22,1	21,9	21,8	21,8
2.	Protected	29,7	29,6	29,5	29,2
3.	Limited production	26,8	26,8	26,8	26,7
4.	Permanent production	29,2	29,2	29,2	29,1
5.	Convertible production	12,8	12,8	12,7	11,08
	Total	120,6	120,3	120,26	118,1

Source: The State of Indonesia's Forest (SOIFO) 2018, 2020, 2022, and 2024

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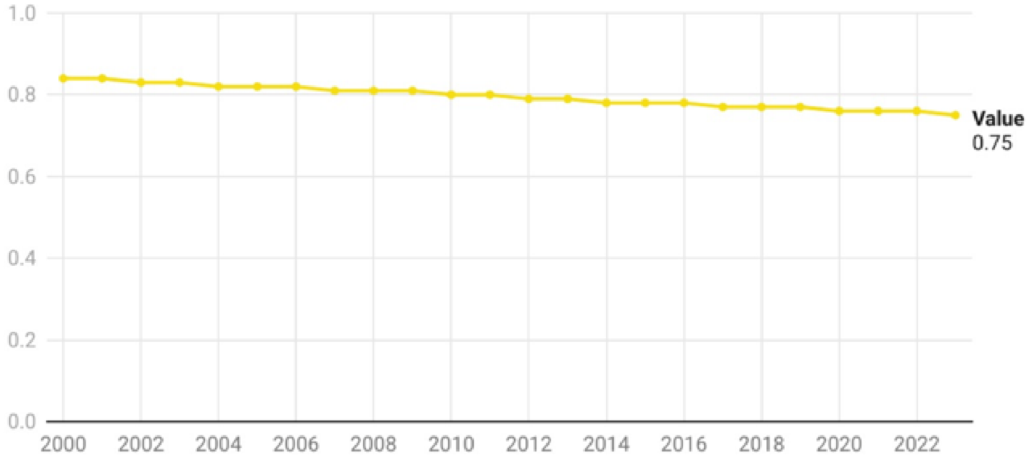
Indonesia is the country with the second highest level of biodiversity in the world (Shmelev 2025). Indonesia is home to 720 mammal species (more than 13% of mammal species in the world), 1.605 bird species (about 16% of the total species in the world), 385 amphibian species (about 6% of the world's amphibian species), 723 reptile species (8% of the world's reptile species), and 1.248 freshwater fish species (8,9% of the world's freshwater fish species) (Maskun *et al.* 2021). In Southeast Asia and South Asia, Indonesia contributes the most endangered species. There are 2.432 endangered species in Indonesia, ranging from mammals and plants to fungi (Oktavianto 2024). The red list index (RLI) also shows that Indonesia's biodiversity is becoming more vulnerable.



Source: Sustainable Development Report of Indonesia 2023 quoted from Azzahra 2024.

Figure 1 RLI Indonesia 2000 – 2022

RLI describes the threat of biodiversity extinction through changes in threat status and species loss, based on International Union for Conservation of Nature (IUCN) data. RLI ranges from 0 to 1, with 0 indicating extinct status or that all species are extinct, and 1 indicating least concern status or very low risk of extinction. Indonesia has experienced a decline in its index value, indicating an increase in the extinction of biodiversity. The government needs to intensify repossession in conservation and protected forests for ecosystem restoration, even though GR 45/2025 does not regulate this.

The second issue highlights the decision binding principles adopted in GR

45/2025. Article 30 verse (3) and Article 35 verse (5) of GR 45/2025 state that administrative fines must be paid no later than 30 days after the issuance of payment order. This provision may deviate from the principle of decision binding because it uses the period since the decision was issued, rather than the period since the decision was received. This provision had already been applied by GR 24/2021, which stipulated that administrative fines must be paid within 6 months from the date of imposition. In accordance with the principle of administrative governance, government officials are required to deliver decisions to the parties adressed. With the acceptance by the intended party, the decision has binding force. Principles for receiving the decision is regulated in Articles 60 and 61 of Law Number 30 of 2014 on Government Administration (Government Administration Law):

"*Article 60*
(1) *A decision shall be binding upon its announcement or upon its receipt by the parties in the Decision.*
(2) In the event of a difference in the time of announcement by the recipient, the Decision shall be binding upon its receipt.
(3) *In the event of a discrepancy in the proof of time of receipt between the sender and the recipient, the binding of the Decision shall be based on the proof of receipt held by the recipient of the Decision, unless otherwise proven by the sender*."

"*Article 61*
(1) Every Decision shall be delivered by the Agency and/or Government Official to the parties mentioned in the Decision."

Based on Articles 60 and 61 of Government Administration Law, it can be concluded that administrative decisions, state administrative decisions, or state administrative decisions must be received by the addressee to be binding. To ensure fairness for legal subjects, the government is required to deliver the decision as soon as possible after the issuance. For some legal subjects, 30 days may be too short to pay administrative fines, especially since GR 45/2025 does not allow legal subjects to make installments. An extension of time is needed to pay administrative fines, for example, for companies experiencing liquidity problems. The government can deliver decisions electronically to accelerate the process. This is regulated in Article 62 of Government Administration Law:

"*Article 62*
(1) Decisions may be delivered by registered mail, courier, or electronic means.
(2) The decision referred to in verse (1) must be immediately delivered to the relevant party or maximum 5 (five) working days of its enactment.
(3) Decisions intended for the public or of a mass nature shall be delivered maximum 10 (ten) working days of their enactment.
(4) Decisions announced through print media, electronic media, and/or other media shall take effect maximum 10 (ten) working days from the issuance.
(5) In the event of a problem with delivery as referred to in verse (4), the relevant Agency and/or Government Official must provide proof of the date of delivery and receipt."

The third issue is the removal of the provision ascertaining that administrative fine is non-tax state revenue (NTSR) of Ministry of Forestry. This provision has serious implications, namely uncertainty regarding which agency that will manages NTSR. It is necessary to appoint an agency for each type of NTSR, as there are several obligations to ensure. Law Number 9 of 2018 on Non-Tax State Revenue (NTSR Law) outlines the obligations of NTSR mana-agency.

Table 6 Obligations of NTSR Management Agencies

No.	Article	Obligation
1.	Article 17 verse (2)	Prepare and submit proposals for the types and rates of NTSR; propose the use of NTSR funds; prepare and submit a NTSR plan for the preparation of the state budget bill and/or revised state budget; collect and deposit NTSR into state treasury; implement the budget sourced from the NTSR fund allocation; manage NTSR receivables; prepare and submit NTSR accountability report; appoint an official to manage NTSR; and carry out other duties regarding NTSR.
2.	Article 27 verse (1)	Verify the receipt of NTSR calculated by the payers.
3.	Article 36 verse (1)	Determining NTSR payable in the event of underpayment.
4.	Article 37 verse (1)	Issue and deliver NTSR invoices to payers if there are outstanding NTSR.
5.	Article 45 verse (1)	Conducting internal oversight of NTSR management.
6.	Article 53 verse (1)	Provide, present, and/or submit documents, information, and/or other evidence requested by the examining agency.
7.	Article 56	If there is a shortfall in NTSR payments, shall follow up by issuing and delivering a letter of determination of NTSR underpayment and a NTSR invoice to the payer. If there is an overpayment, shall issue a NTSR overpayment letter and deliver notification to the payers.
8.	Article 58 verse (1)	Receiving objection files from payers regarding: NTSR assessment letters for underpayment; NTSR assessment letters for zero payment; or NTSR assessment letters for overpayment.
9.	Article 59 verse (3)	Issue a decision on the objection maximum 6 months after the objection letter and supporting documents received completely.
10.	Article 62 verse (1)	Receiving documents requesting relief from NTSR owed by payers.
11.	Article 63 verse (2)	Receiving files requesting refunds for overpayments of NTSR submitted by payers.

Source: NTSR Law.

There is still uncertainty as to whether administrative fines will become NTSR for Ministry of Forestry, NTSR for the Attorney General's Office, or NTSR for other agencies. Based on Article 44 verse (2) GR 45/2025, the state attorney is responsible for collecting administrative fines, seizing assets, and auctioning off seized goods through the state auction office in cases where administrative fines are not paid after assets have been seized. This absurdity can lead to mismanagement, for example, who will prepare and submit NTSR plan to Ministry of Finance; who will manage NTSR receivables; who will prepare and submit NTSR accountability report; and who will receive requests for objections, relief, or refunds of NTSR from taxpayers? This issue needs to be mitigated immediately by the government by determining which agency is designated to manage the NTSR.

CONCLUSION

The study identifies four new provisions in GR 45/2025, namely strengthening the role of the Forest Area Order Task Force; revising the administrative fine formula; introducing instruments for repossessing forest areas; and removing the legality of continuing business under the provisions of Article 110B. There are three crucial issues that have the potential to cause legal uncertainty, namely the lack of clarity on follow-up actions for repossession in conservation and protected forests; the weak principle of enforceability of administrative sanction decisions; and the lack of clarity on the agency that manages NTSR from administrative fines. There are three research recommendations for the government, namely to intensify the repossession of conservation forests and protected forests for ecosystem restoration; to develop a system for delivering administrative sanction quickly to legal subjects; and to appoint an agency to manage NTSR.

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INTERNATIONAL JOURNAL of OIL PALM

Volume 9, Number 1, 2026
Page 20–30
DOI: 10.35876/ijop.v9i1.159

ISSN: 2599-3496 print
ISSN: 2614-2376 online

Valorization of Palm Oil Mill Effluent (POME) for Renewable Energy: A Systematic Review on Biogas Potential and Policy Implications in Indonesia

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ABSTRACT

Palm Oil Mill Effluent (POME) represents one of the most significant by-products of the palm oil industry, often perceived as a major environmental pollutant due to its high organic load and greenhouse gas (GHG) emissions. However, its valorization as a biogas source offers a promising pathway toward sustainable energy transition in Indonesia. This study presents a systematic literature review (SLR) to evaluate the biogas potential of POME and to explore policy frameworks that support its implementation in the Indonesian context. The review was conducted based on PRISMA guidelines by screening peer-reviewed articles from 2013 to 2024 using databases such as Scopus, ScienceDirect, and Google Scholar. A total of 38 relevant studies were analyzed, covering techno-economic feasibility, conversion efficiency, environmental impacts, and regulatory perspectives. Findings indicate that POME has a high potential for biogas production, with methane yields ranging between 15–28 m³ per m³ of POME under optimized anaerobic digestion processes. Furthermore, several pilot-scale and industrial implementations in Sumatra and Kalimantan demonstrate technical viability. However, challenges remain in terms of infrastructure investment, fragmented policies, and lack of integration with national energy targets. Current regulations, including the Presidential Regulation on Renewable Energy and Ministry of Energy's roadmap, provide a partial foundation, but clearer incentives and decentralized support mechanisms are needed. This review highlights the urgency of aligning technological potential with comprehensive policy support to accelerate the adoption of POME-to-biogas initiatives, especially among small and medium-scale palm oil mills. The valorization of POME not only contributes to Indonesia's renewable energy mix but also addresses environmental and socio-economic concerns within the palm oil sector.

Keywords: Biogas, policy; palm oil mill effluent; renewable energy; systematic literature review; waste valorization

INTRODUCTION

Indonesia is the world's largest producer of crude palm oil (CPO), cultivating more than 13 million hectares and producing over 50 million tonnes annually (GAPKI 2023; Ministry of Agriculture 2022). The palm oil industry plays a vital role in national development,

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contributing approximately 3.5% to GDP and providing livelihoods for millions of people across rural and industrial value chains (World Bank 2021; Santika *et al.* 2019). At the same time, the rapid expansion of the sector has engendered a range of environmental issues, including land degradation, biodiversity loss, and the generation of large volumes of organic waste most notably Palm Oil Mill Effluent (POME).

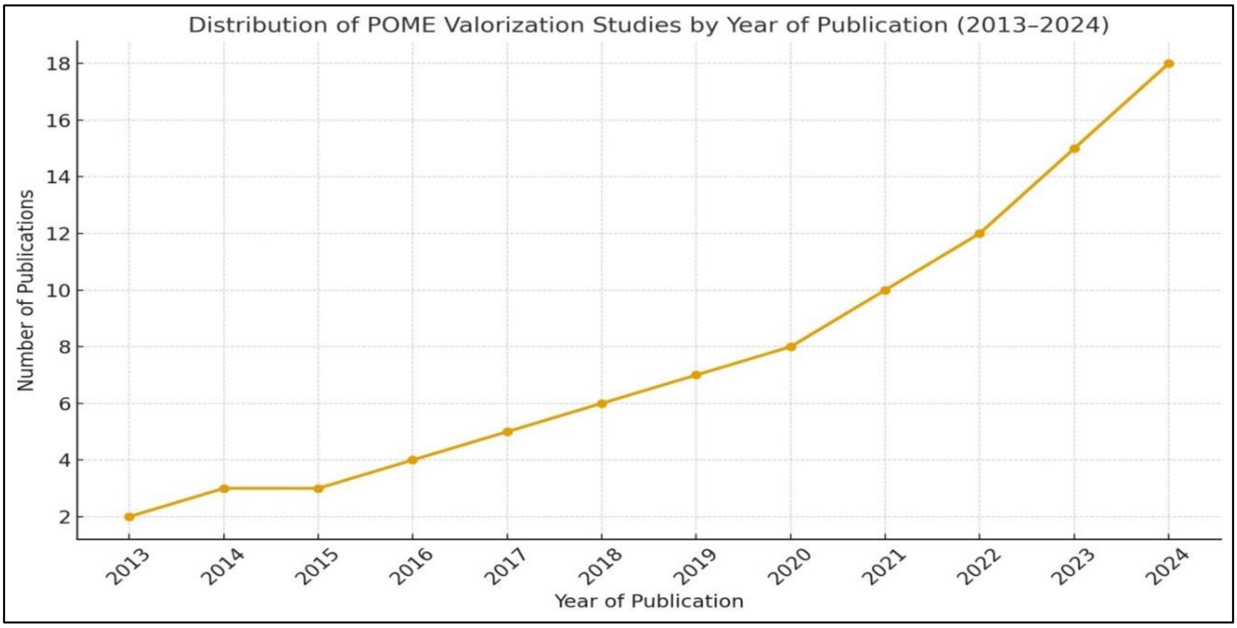
POME is the liquid by product of sterilization and clarification during the palm oil extraction process. Typical production rates are on the order of 2.5–3.0 m³ of POME per tonne of CPO (Nasution *et al.* 2020; Ma *et al.* 2021). POME contains high concentrations of suspended solids, fats, oils and grease, exhibiting elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) that can seriously impair aquatic ecosystems if discharged untreated (Yacob *et al.* 2005; Wu *et al.* 2009; Abdurrahman *et al.* 2022). Moreover, conventional open pond treatment systems emit significant greenhouse gases (GHGs), particularly methane (CH_4), which contributes to the industry's climate footprint (Chin *et al.* 2013; Zakaria *et al.* 2020). Paradoxically, the very charac-teristics that make POME an environ-mental liability its high organic load also make it an attractive substrate for anaerobic digestion and biogas production (Kamyab *et al.* 2021; Rajagopal *et al.* 2013). Reported methane yields vary depending on feedstock composition, pretreatment, reactor design, and operational conditions; typical values from reviewed studies range from approxi-mately 15 to 28 m³ CH_4 per m³ of POME under optimized conditions (Lam *et al.* 2021; Iskandar *et al.* 2022; Wong *et al.* 2019). If effectively harnessed, biogas from POME can supply electricity, process heat, or even upgraded biomethane for transport, while reducing methane emissions from open systems (IEA 2022; Mohammed *et al.* 2023). To contextualize the technical attributes of POME, Table 1 summarizes average composition parameters and reported biogas yields compiled from previous studies. This baseline information underscores both the energetic potential of POME and the variability that practitioners must manage in implementation.

Table 1 Average Composition of POME and its Biogas Potential.

Parameter	Average Value	Range	Source
Volume POME/CPO	2.5 – 3.0 m³ per ton	2.0 – 3.5 m³/ton	Nasution *et al.* (2020); Ma *et al.* (2021)
BOD	25,000 – 65,000 mg/L	20,000 – 100,000	Yacob *et al.* (2005); Hassan *et al* (2019)
COD	50,000 – 100,000 mg/L	40,000 – 110,000	Wu *et al.* (2009); Abdurrahman *et al.* (2022)
pH	4.0 – 5.5	-	Wong *et al.* (2019)
CH_4 Yield (anaerobic)	15 – 28 m³ CH_4/m³ POME	10–35 m³/m³	Lam *et al.* (2021); Iskandar *et al.* (2022)

Beyond technical feasibility, POME-to-biogas development sits within Indonesia's broader policy landscape for energy transition and climate mitigation. National targets such as achieving 23% renewable energy in the primary energy mix by 2025 and pursuing net-zero emissions pathways by mid-century create institutional incentive structures for bioenergy deployment (Kementerian ESDM, 2023; Presidential Regulation No. 112/2022). Nonetheless, adoption at scale particularly among small and medium-sized mills remains constrained by barriers including high upfront capital costs, limited technical capacity, fragmented regulatory incentives, and logistical challenges in connecting decentralized biogas assets to energy systems (Ginting *et al.* 2020; Saragih *et al.* 2021; Hasanah *et al.* 2022).

The academic literature on POME valorization has expanded considerably in recent years. Figure 1 illustrates the number of publications addressing POME and biogas production between 2013 and 2024, indicating growing research interest. However, the literature is largely fragmented: many studies concentrate on reactor design, pretreatment, and yield optimization, while others analyze policy instruments or economic viability in isolation. To our knowledge, there remains no systematic review that integrates both the technical potential and the policy frameworks required for widespread POME-to-biogas adoption in Indonesia.



Source: Data compiled by author from 38 (Lam *et al.* 2021; Iskandar *et al.* 2022; GAPKI 2023, etc.) reviewed studies (Appendix Table 6)

Figure 1 Distribution of POME Valorization Studies by Year Publication (2013–2024)

This fragmentation represents a critical gap. Given intensified international scrutiny of palm oil sustainability (European Commission 2023; Mongabay 2022), a synthesis that bridges techno-economic evidence and policy analysis is needed to inform both practitioners and policymakers. Constructing a science-based narrative around POME valorization can both reduce environmental impacts and support the sector's socio-economic resilience (UNEP 2022; Cahyadi and Waibel 2021). Therefore, this paper presents a Systematic Literature Review of studies published between 2013 and 2024, with the following objectives: (1) To identify and evaluate the technical potential of converting POME into biogas based on peer-reviewed evidence; (2) To analyze key barriers and success factors in implementation across pilot, commercial and smallholder scales; and (3) To examine the extent to which national policies and regulatory frameworks support or hinder the adoption of POME to-biogas technologies.

By integrating evidence across technical, economic, and policy domains, this review aims to contribute to scholarly discourse, inform pragmatic policy recommendations, and support wider adoption of sustainable energy practices in Indonesia's palm oil sector.

MATERIALS AND METHODS

This study employed a Systematic Literature Review (SLR) approach guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher *et al.* 2009). The purpose was to ensure transparency, replicability, and scientific rigor in identifying, evaluating, and synthesizing the literature on POME-to-biogas in Indonesia.

Research Questions

The review was designed to address three guiding research questions (RQ) at Table 2.

Table 2 Research Questions of this Study

RQ	Research Question	Focus
RQ1	What is the technical potential of converting POME into biogas in Indonesia?	Methane yield, reactor types, operating conditions.
RQ2	What are the key barriers and success factors in implementing POME-to-biogas systems?	Financial, infrastructural, institutional, and social aspects.
RQ3	How do existing policies and regulations support or hinder adoption?	National targets, renewable energy incentives, regulatory gaps.

Search Strategy

A comprehensive search was conducted across three major scientific databases: Scopus, ScienceDirect, and Google Scholar. The search covered literature published from January 2013 to March 2024. Boolean operators were used to maximize coverage, with combinations such as:

1. "POME" and "biogas" and "Indonesia"
2. "Palm Oil Mill Effluent" and "Anaerobic Digestion"
3. "Biogas Policy" and "Renewable Energy" and "Palm Oil"
4. "Waste to Energy" and "Palm Oil Industry".

Only peer-reviewed journal articles, conference proceedings, and government-backed policy reports were included. Non-English documents, non-academic articles, and studies without full text access wer.

Inclusion and Exclusion Criteria

A comprehensive search was conducted across three major scientific databases: (1) Scopus, (2) ScienceDirect, and (3) Google Scholar at Table 3.

Table 3 Inclusion and Exclusion Criteria Applied in Article Selection

Category	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed journals, proceedings, official policy reports	Blogs, news, opinion, piece, non-academic reports
Language	English	Non-english
Time Frame	2013-2024	< 2013
Scope	Technical studies on POME-to-biogas; Policy/regulations on renewable energy	Non-palm oil biomass, unrelated renewable energy studies
Availability	Full-text accessible	Abstract only, inaccessible full-text

Screening Process

The initial search yielded 217 documents. After removing duplicates and irrelevant records, 81 articles were retained for full-text screening. Based on the inclusion/exclusion criteria, 38 studies were selected for detailed analysis. The selection process is illustrated in Figure 2 (PRISMA flow diagram).

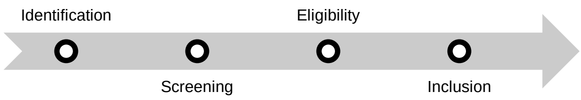


Figure 2 PRISMA Flow Diagram of Literature Selection Process.

Data Extraction and Thematic Analysis

The final set of 38 articles was analyzed using a structured matrix to capture both technical and policy-related dimensions. Data extraction focused on:

1. Technical parameters: methane yield, digestion conditions, reactor type, pretreatment.
2. Implementation scale: pilot, industrial, SME/community-based.
3. Barriers and enablers: financial, infrastructure, regulatory, and socio-technical support.
4. Policy context: alignment with national renewable energy targets, subsidies, incentives, and institutional frameworks. The extracted data were tabulated and coded thematically, allowing cross study comparison and synthesis into broader analytical categories.

RESULTS AND DISCUSSION

This section synthesizes findings from the 38 studies retained in the SLR. Results are presented in three thematic clusters aligned with the research questions: (1) technical potential of POME-to-biogas conversion, (2) implementation experiences and challenges, and (3) policy and regulatory frameworks.

Technical Potential of POME-to-Biogas Conversion

The reviewed studies consistently demonstrate the high potential of POME as a substrate for anaerobic digestion. Across 25 technical papers, reported methane yields range between 15–28 m^3 CH_4/m^3 POME, with several studies reporting optimized values up to 35 m^3 CH_4/m^3 under controlled conditions (Lam *et al.* 2021; Iskandar *et al.* 2022). Reactor design significantly influences yield: continuous stirred-tank reactors (CSTRs) and upflow anaerobic sludge blanket (UASB) reactors consistently outperformed open pond systems. Pretreatment methods such as pH adjustment and co-digestion with agro-residues improved methane recovery by 15–25% compared to untreated POME (Wong *et al.* 2019). The following results are available in Table 4.

Table 4 Summary of Reported Methane Yields and Reactor Types.

Study Range	Reactor Type	Methane Yield (m^3 CH_4/m^3 POME)	Key Notes
Pilot Scale (n=12)	Open Pond	8−15	High GHG Emissions, Low Control
Pilot Scale (n=6)	UASB	18−25	Improved COD Removal, Stable
Industrial Case (n=5)	CSTR	20−28	High Capital Costs, Scalable
Laboratory Trials (n=7)	Hybrid/Pretreatment	25−35	Co-digestion Enhances Yield

The findings confirm that while technical viability is proven, the choice of reactor technology strongly affects efficiency and investment requirements.

Implementation Experiences and Challenges

Among the 38 reviewed papers, 11 focused on field applications at pilot or industrial scale. Case studies from Sumatra and Kalimantan showed that biogas plants can offset up to 20–40% of mill electricity demand when integrated with existing operations (Nasution *et al.* 2020; Tan *et al.* 2020). However, diffusion among small and medium enterprises (SMEs) remains limited. High upfront investment (USD 2–5 million per plant), lack of technical expertise, and maintenance costs are recurrent barriers (Hasanah *et al.* 2022). Several projects collapsed after 2–3 years due to inadequate operator training and absence of local supply chains for spare parts. The following results are available in Figure 3.

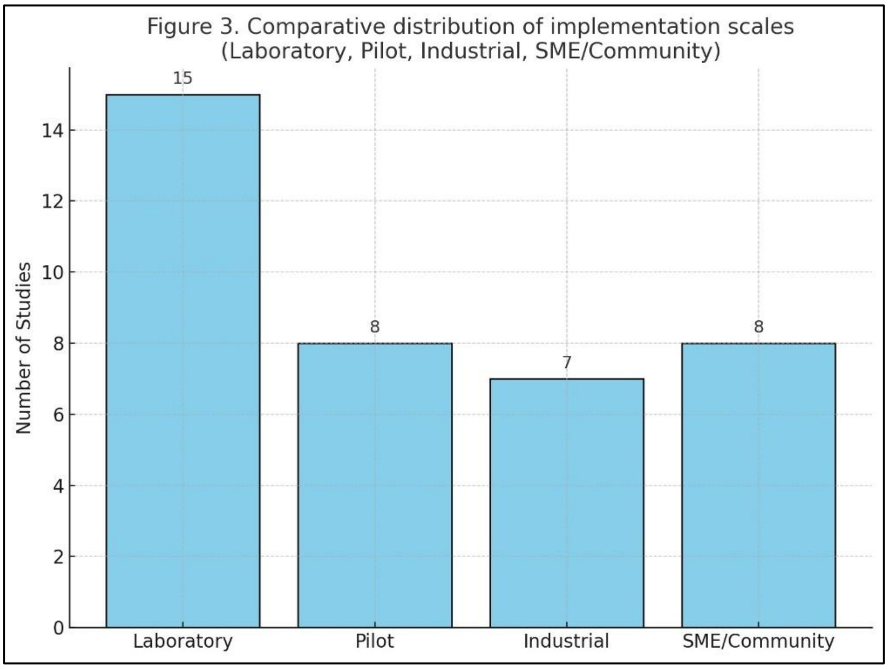


Figure 3 Comparative Distribution of Implementation Scales (Laboratory, Pilot, Industrial, SME/Community).

Importantly, five studies documented co-benefits beyond energy: reduction of COD/BOD by 80–95%, mitigation of methane emissions by up to 90%, and socio-economic gains from job creation and community electrification (Chin *et al.* 2013; Saragih *et al.* 2021).

Policy and Regulatory Frame-works

A total of 12 papers examined the policy landscape. Indonesia's renewable energy roadmap and Presidential Regulation No. 112/2022 provide a partial framework for bioenergy, yet explicit incentives for POME-to-biogas remain fragmented (Widiyanto and Pranowo, 2020; Setyawan *et al.* 2022). The following results are available in Table 5.

1. Positive signals: Feed-in tariffs for biomass, inclusion of bioenergy in National Energy Policy, pilot subsidies from BPDPKS.
2. Limitations: lack of decentralized support, inconsistent enforcement across provinces, absence of targeted SME financing.
3. Comparative evidence: Malaysia's centralized incentive schemes and Thailand's community biogas models were cited as successful references (Rajagopal *et al.* 2013; UNEP 2022).

Table 5 Policy Enablers and Barriers Identified in the Literature.

Dimension	Enablers	Barriers
Financial	Feed-in tariff, green fund grants	High upfront capital, limited SME credit
Institusional	Renewable energy roadmap, BPDPKS support	Fragmanted coordination among ministries
Technical	Demonstration projects in Sumatera, Kalimantan	Lack of skilled operators, weak O&M support
Regulatory	National target 23% RE by 2025	No specific POME-to-biogas mandate, inconsistent enforcement

Integrated Discussion

Synthesizing across technical, implementation, and policy dimensions reveals a paradox: while the technical potential of POME-to-biogas is well established, implementation remains uneven due to fragmented policies and financial barriers:

1. Technically, optimized anaerobic digestion can generate 25–35 m³ CH_4/m³ POME, equivalent to ~2.5 GJ energy per tonne CPO, positioning POME as a strategic renewable source.
2. Socio-environmental benefits are clear, yet SMEs who operate ~60% of Indonesian mills remain excluded from adoption.
3. Policy frameworks exist but lack targeted, integrated, and enforceable instruments.

This gap suggests that the transition from technical viability to mainstream adoption requires:

1. Financial de-risking instruments (soft loans, blended finance for SMEs).
2. Decentralized policy support at provincial level.
3. Capacity building programs for plant operation and maintenance.
4. Integration into carbon markets to monetize methane reductions

CONCLUSION

This study conducted a Systematic Literature Review (SLR) of 38 peer-reviewed publications from 2013 to 2024 to evaluate the potential of Palm Oil Mill Effluent (POME) as a renewable energy resource in Indonesia. Three major insights emerged from the analysis.

First, the technical feasibility of POME-to-biogas conversion is well established. Across laboratory, pilot, and industrial studies, methane yields consistently ranged from 15–28 m³ CH_4/m³ POME, with optimized systems achieving up to 35 m³/m³. Advanced reactor configurations (e.g., CSTR, UASB) and pretreatment strategies significantly enhanced efficiency compared to conventional open pond systems.

Second, implementation at scale remains uneven. While industrial-scale plants demonstrate clear benefits—reducing COD/BOD by 80–95%, mitigating methane emissions by up to 90%, and supplying 20–40% of mill electricity demand—adoption among small and medium enterprises (SMEs) is minimal. High capital costs, limited technical expertise, and weak local supply chains continue to hinder diffusion, resulting in project failures and underutilized potential.

Third, the policy and regulatory landscape is fragmented. Despite Indonesia's commitment to achieve 23% renewable energy by 2025 and net-zero by 2060, existing instruments provide only partial support for POME valorization. Unlike Malaysia and Thailand, where structured feed-in tariffs and community-based biogas models have been implemented, Indonesia lacks targeted financial de-risking, decentralized enforcement, and long-term incentives for SMEs.

Taken together, these findings highlight a critical paradox: the technical potential of POME-to-biogas is proven, but its widespread adoption remains constrained by financial, institutional, and policy gaps. This review underscores the need for integrated strategies that combine: (i) financial instruments such as blended finance or carbon market integration, (ii) decentralized policy implementation at the provincial level, and (iii) sustained capacity building for operators and SMEs.

By synthesizing technological evidence and policy analysis, this study contributes to scholarly discourse and provides a roadmap for aligning POME valorization with Indonesia's climate and energy transition agenda. Future research should focus on long-term monitoring of operational plants, comparative policy effectiveness across Southeast Asia, and innovative financing mechanisms that can unlock POME's full potential as a cornerstone of sustainable palm oil production.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to University of Mercu Buana and University of Singaperbangsa Karawang for the academic guidance and resources provided throughout the completion of this study. Special appreciation is extended to the Faculty of Engineering, which facilitated access to scientific databases and provided critical feedback during the research process. The authors also acknowledge the valuable contributions of colleagues and peers who assisted in refining the systematic review protocol and offered insightful discussions on both technical and policy perspectives of POME-to-biogas development.

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Appendix

Appendix Table 6. Summary of 38 Reviewed Studies on POME-to Biogas (2013-2024)

Table A1 Summary of 38 Reviewed Studies on POME-to Biogas (2013-2024)

.No	Author(s), Year	Location	Focus/Theme	Main Findings
1	Ji C. May *et al.* 2013	Malaysia	National perspective on POME biogas	Identified technical & policy opportunites, highlighted limited adoption at SMEs
2	Choi W. H. *et al.* 2013	Malaysia	High-rate anaerobic reactor systems	Combined reactor approach improved COD removal (>80%) and methane yield up to 22 m^3/m^3
3	Rajagopal R. *et al.* 2013	Thailand	Anaerobic digestion review	Comparative review; stressed effieciency of CSTR vs. lagoons; barriers for community plants
4	Ahmed T. *et al.* 2015	Multi-Country	Review of POME-to-biogas	Summarized anaerobic systems; yields 15-28 m^3 CH_4/m^3 POME under mesophilic conditions
5	Hasanudin U. *et al.* 2015	Indonesia (Lampung)	Pilot biogas plant trials	COD reduction ~85%; methane captured for boiler fuel; challenges in O&M noted
6	Ohimain E. I., 2017	Global	State-of-art-review	Categorized reactor types; highlighted environmental benefits & socio-economic barriers
7	Pleanjai & Gheewala, 2017	Thailand & Malaysia	Techno-economic assessment	Life-cycle analysis; biogas competitive if FIT available; SMEs constrained
8	Khairuddin *et*	Malaysia	Co-digestion	Co-digestion increased

	al. 2018		(EFB + POME)	methane yield 18-22% vs. POME alone
9	Wong L. P. *et al.* 2019	Malaysia	Pretreatment effect	Pretreatment & pH adjustment raised methane yield up to 30 m^3/m^3
10	Suprihatin *et al.* 2019	Indonesia	Temperature effects	Methane yield at 27ºC: 0.19 m^3, 45ºC: 0.25 m^3, 55ºC: 0.28 m^3; optimal mesophilic
11	Tan Y. *et al.* 2020	Indonesia	Techno-economic analysis	IRR positive only with subsidies; CAPEX ~USD 3-5 million/plant
12	Ginting *et al.* 2020	Indonesia	SME adoption barriers	Identified financing gap, lack of local expertise, limited space parts supply
13	Widiyanto & Pranowo, 2020	Indonesia	Policy evaluation	National energy roadmap partial; no specific POME mandates
14	Lam M. K. *et al.* 2021	Malaysia	Reactor optimization	CSTR yielded 28-35 m^3 CH_4/m^3 POME; UASB ~22-25 m^3
15	Iskandar *et al.* 2021	Indonesia	Pilot anaerobic digester	Methane yield ~20 m^3/m^3; COD reduction >90%
16	Foong S. Z. Y. *et al.* 2021	Malaysia	Systems approach	Recommended bundled incentives, stronger monitoring, integration with mills
17	Saragih *et al.* 2021	Indonesia	Socio-economic impacts	Documented electrification in Kalimantan village;created 20+ local jobs
18	Sulaiman *et al.* 2021	Indonesia	AD performance	Thermophilic digester increased COD removal efficiency by 10-15%
19	Khadaroo S. N. B. A. *et al.* 2021	Malaysia	CSTR optimization	Solid-liquid ratio adjustment improved methane yield by 12%
20	Singkala A. *et al.* 2021	Thailand	pH adjustment (thermophilic AD)	Using oil palm ash for pH balance improved digester stability
21	Setyawan *et al.* 2022	Indonesia	Policy & institutional	Found fragmented enforcement; proposed integrated agency support
22	Sodri A. *et al.* 2022	Indonesia (Bangka)	Techno-economic case study	COD reduced 91%; CH_4 ~55%; electricity 696,163 kWh/mo; IRR 6.75%
23	Isa M. H. *et al.* 2022	Malaysia	Ultrasound pretreatment	Enhanced microbial activity; methane yield up 20%
24	Rashidi N. A. *et al.* 2022	Malaysia	Biomass energy policy	Barriers: inconsistent FIT, low uptake in SMEs
25	Abdurrahman *et al.* 2022	Indonesia	Pollutant load study	POME COD up to 110,000 m/L; untreated discharge risk high

26	Hidayatullah I. M. *et al.* 2023	Indonesia	Simulation biomethane	Modeled upgrading system; purity >95% CH_4 possible
27	Mohammed *et al.* 2023	Nigeria	Transportation fuel potential	POME biogas viable for CNG buses; case study of substitution benefits
28	Cahyadi & Waibel, 2023	Indonesia	Socio-economic narrative	POME valorization improves palm oil reputation in EU market
29	UNEP, 2022	Global	Sustainability & SDGs	Framed POME biogas as climate mitigation + circular economy
30	European Commission, 2023	EU/Global	Policy & trade pressure	Highlighted palm oil sustainability scrutiny affecting exports
31	Mongabay, 2023	Indonesia	Environmental reporting	Critiqued deforestation, carbon emissions in palm sector
32	GAPKI, 2023	Indonesia	Industry stats	50+ million tons CPO, 13M ha; scale of waste streams
33	Kementrian ESDM, 2023	Indonesia	Energy policy target	23% renewable mix by 2025; net-zero 2060
34	Presidential Regulation 112/2022	Indonesia	Renewable framework	Regulation includes bioenergy but no direct POME incentive
35	BPPT, 2020	Indonesia	Bioenergy roadmap	Included POME but limited pilot rollout
36	DGNREEC, 2021	Indonesia	Renewable energy policy	Positioned POME biogas as strategic resource
37	Ng H. J. *et al.* 2024	Malaysia	Microbial community	Showed microbial diversity explains yield variability
38	Salehmin M. N. I. *et al.* 2024	Malaysia	Comparative review	Synthesized 2019-2024 AD performance & policy gaps

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A short communication is a condensed version of research article, written without chapters, up to 3500 words (including table and figures in good resolution). It consists of title, authors name and affiliations, abstract, keywords, main content, and references. The main content of the article should represent introduction, materials and method, result and discussion, and conclusion, prepared without headings. A short communication should contribute an important novelty for science, technology, or application.

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a. The manuscript should be written in a good English. It must be type written on A4 paper by using Microsoft Word processor with Arial font 12 and 1.15 spaced.
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d. The manuscript has not been published in any proceeding of scientific meeting or conference.
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a. The title of the article should be brief and informative (max. 10 words) in Arial font 16 and 1.15 spaced.
b. Each word of the title is initiated with capital letter, except for the species name of organisms.
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a. Abstract written in one paragraph in English and 250 to 300 words.
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Content, Tables and Figures

Content includes introduction, materials and methods; result and discussion, conclusion, acknow-ledgement, and references.

Example:

Figure 6 Experiment on incubation time of recombinant manCK7 for palm kernel meal treatment:

a. at 1 hour until 5 hour, and

b. 4 hour until 16 hour. Blanko = PKM treated with buffer phosphate pH 7, enzyme = PKM treated with recombinant manCK7.

Introduction

The introduction states background of the research, including its novelties, supported mainly by the relevant references and ended with the objectives of the research.

Materials and Methods

a. The materials used should include manufacture and source. Specific instruments and equipment should be described clearly.
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c. Any modified procedures of the cited methodology should be explained clearly indicating which parts modifications had been made.
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d. Statistical data in figures and tables must include standard deviation (SD) or standard error of mean (SEM) or other statistical requirements.

Conclusion

Conclusion is drawn based on the objectives of the research.

Acknowledgement (if necessary)

Acknowledgement contains the institution name of funding body/grants /sponsors or institution which provides facilities for the research project, or persons who assisted in technical work and manuscript preparation.

References

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Pahan I, Gumbira-Sa'id E,Tambunan M. 2011. The future of palm oil industrial cluster of Riau region Indonesia. Eur J Soc Sci. 24(3):421-431.

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Book chapter

References for chapters or other parts of a book follow the order Author(s). Year. Chapter title. In: Editor(s). Book title. Place of publication: publisher. Page numbers for that chapter.

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(Based on Presidential Regulation No. 61/2015)

- Food Security, Downstream Market Development and Biodiesel Supply
- Replanting
- Facilities, Infrastructures, and Farmers Empowerment
- Human Resources Development
- Research and Development
- Promotion and Advocacy

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Support Biodiesel Mandatory Program to strengthen Indonesia energy security and the use of renewable energy.

Replanting Program
Support replanting program for smallholders farmers to increase productivity and welfare and to avoid land use, land-use change and forestry (LULUCF).

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