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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 m^3 per m^3 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).

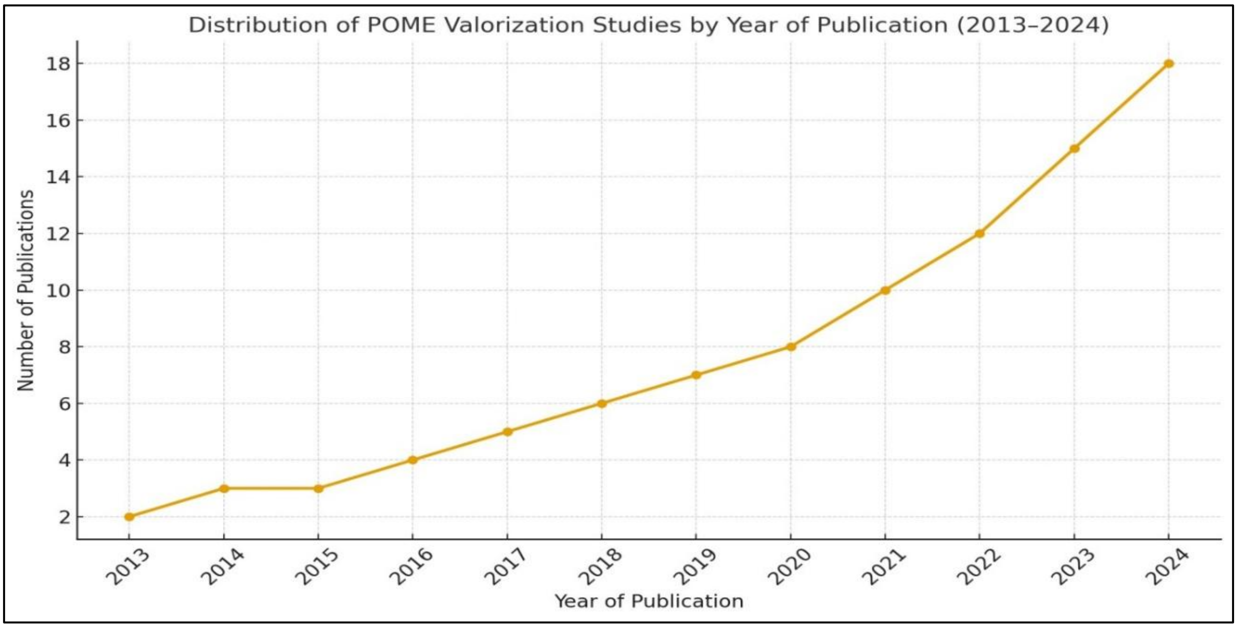
POME is the liquid by product of sterilization and clarification during the palm oil extraction process. Typical production rates are on the order of 2.5–3.0 m³ of POME per tonne of CPO (Nasution *et al.* 2020; Ma *et al.* 2021). POME contains high concentrations of suspended solids, fats, oils and grease, 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 approximately 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 m^3 per ton	2.0 – 3.5 m^3/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 m^3 CH_4/m^3 POME	10–35 m^3/m^3	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).

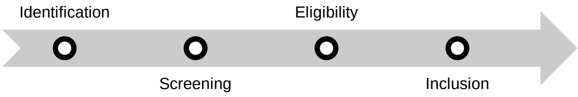


Figure 2 PRISMA Flow Diagram of Literature Selection Process.

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.

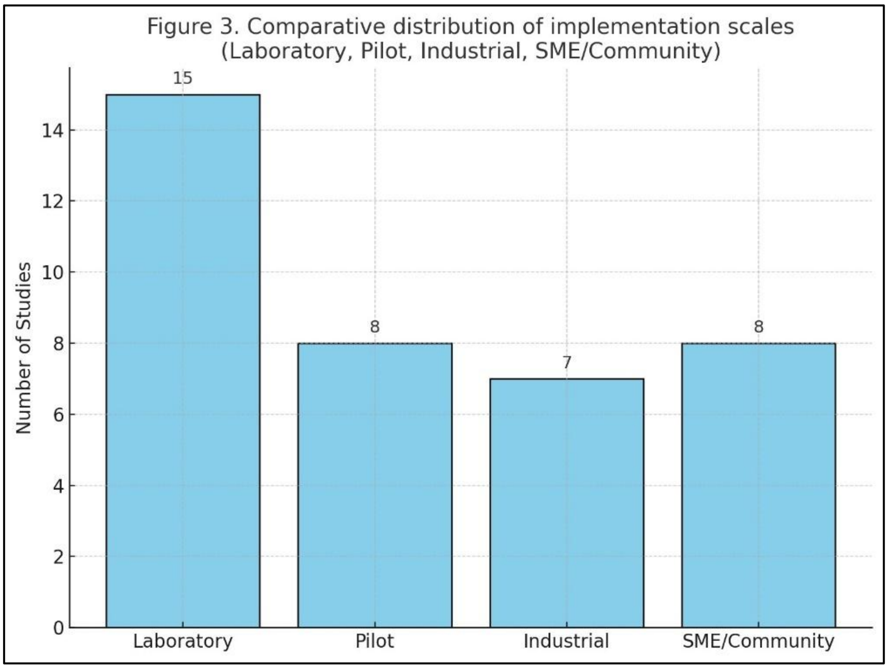


Figure 3 Comparative Distribution of Implementation Scales (Laboratory, Pilot, Industrial, SME/Community).

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.

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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