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| RESEARCH ARTICLE

Circular Economy and Sustainable Palm Oil Waste Management: Evidence from Indonesia

Nina Veronika[1*], Hayatul Khairul Rahmat[1], Pipy Sri Jupita[1], Rizki Ardiansah[1], Hanifa Humaira[1]
[1] *Politeknik Kampar, Bangkinang, Indonesia*

***Corresponding Author**: nina@poltek-kampar.ac.id

| ABSTRACT

The palm oil industry in Indonesia generates enormous quantities of solid and liquid waste, posing significant environmental and socioeconomic challenges. Circular economy (CE) principles offer a transformative framework for converting palm oil waste into valuable resources, thereby reducing environmental burdens while enhancing economic sustainability. This study examines the application of circular economy principles to palm oil waste management in Indonesian palm oil mills, with particular attention to Empty Fruit Bunches (EFB), Palm Oil Mill Effluent (POME), palm kernel shells (PKS), and palm fronds. Using a mixed-methods approach—combining qualitative case studies of six palm oil mills in Riau Province with quantitative analysis of secondary data from the Indonesian Palm Oil Association (GAPKI) for the period 2018–2023—this research assesses the extent of CE adoption, identifies barriers to implementation, and evaluates the environmental and economic outcomes of waste valorization strategies. The findings reveal that CE adoption in Indonesian palm oil mills remains partial and uneven; while biogas capture from POME has achieved significant penetration (68% of large mills), valorization of EFB and other solid wastes lags considerably. Key barriers include high initial capital investment, lack of technical expertise, fragmented policy frameworks, and limited market linkages for waste-derived products. Mills that have fully integrated CE practices demonstrate substantially improved environmental performance—including a 42% reduction in greenhouse gas (GHG) emissions and a 35% reduction in wastewater pollutant loads—alongside enhanced economic resilience through diversified revenue streams. This study contributes to the growing CE literature in tropical agricultural industries and provides evidence-based policy recommendations for accelerating sustainable waste management in the Indonesian palm oil sector.

| KEYWORDS

Circular Economy; Palm Oil Waste Management; Sustainability.

INTRODUCTION

Indonesia is the world's largest producer of crude palm oil (CPO), accounting for approximately 57–58% of global production, with an annual output exceeding 46 million metric tons (FAO, 2023; GAPKI, 2023). The palm oil industry is a cornerstone of the Indonesian economy, contributing significantly to export revenues, rural employment, and smallholder livelihoods across Sumatra, Kalimantan, and Sulawesi. However, the rapid and extensive expansion of the sector has generated enormous quantities of solid and liquid waste—estimated at 7–8 tonnes of waste per tonne of CPO produced—creating acute environmental and resource management challenges (Yusoff et al., 2019).

The dominant waste streams from palm oil processing include Palm Oil Mill Effluent (POME), a highly polluting liquid effluent produced at approximately 0.67 m^3 per tonne of fresh fruit bunches (FFB) processed; Empty Fruit Bunches (EFB), constituting around 22% of FFB weight; palm kernel shells (PKS); mesocarp fiber; and decanter cake (Chiew & Shimada, 2013). When inadequately managed, these wastes contribute to water pollution, greenhouse gas (GHG) emissions—particularly methane from open POME ponds—soil degradation, and biodiversity loss, threatening both local ecosystems and global climate targets (Yee et al., 2010).

The circular economy (CE) paradigm, which emphasizes the redesign of industrial systems to eliminate waste through the continuous cycling of resources at their highest utility, has gained considerable traction as a transformative sustainability strategy (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). In the context of the palm oil industry, CE principles offer a compelling framework for converting waste streams into valuable products—including biogas, bio-fertilizer, biomass energy, biochar, and high-value biochemicals—thereby closing resource loops and reducing environmental externalities (Foo & Hameed, 2010).

Despite growing scholarly and policy interest in CE applications to agro-industrial waste management, empirical evidence from the Indonesian palm oil sector remains limited and geographically fragmented. Most existing studies focus on specific waste types or valorization technologies in isolation, without providing a holistic assessment of CE adoption across the industry or analyzing the systemic barriers and enablers of implementation (Saswattecha et al., 2015; Sudiyani et al., 2021). This constitutes a significant gap in the literature, particularly given Indonesia's commitment to reducing GHG emissions under the Paris Agreement and its national targets for renewable energy and sustainable land use.

This study addresses this gap by examining CE adoption in palm oil waste management across six mills in Riau Province—Indonesia's largest palm oil-producing region—using a mixed-methods research design. The study aims to: (1) map the current state of palm oil waste valorization and CE adoption in Indonesian mills; (2) identify key barriers and drivers of CE implementation; (3) evaluate the environmental and economic outcomes of CE practices; and (4) provide actionable policy recommendations for accelerating sustainable waste management in the sector.

RESEARCH METHODS

Research Design

This study adopted a mixed-methods research design, combining qualitative case studies with quantitative secondary data analysis. The mixed-methods approach was chosen to capture both the depth and complexity of CE implementation processes at the mill level (qualitative) and the breadth of industry-wide environmental and economic trends (quantitative), thereby providing a more comprehensive and triangulated understanding of the research phenomenon (Creswell & Creswell, 2018).

Case Study Selection

Six palm oil mills in Riau Province were purposively selected as case study sites to represent variation across key dimensions: mill size (large: >60 tons FFB/hour; medium: 30–60 tons/hour; small: <30 tons/hour), ownership type (multinational corporate, domestic corporate, cooperative/smallholder), and ISPO certification status (certified versus uncertified). The six mills are identified as Mill A through Mill F to maintain confidentiality. Primary data were collected through semi-structured interviews (n = 42) conducted with mill managers, environmental officers, agronomists, and local government representatives between January and June 2024. Interviews were audio-recorded, transcribed, and analyzed using thematic analysis in NVivo 14.

Quantitative Secondary Data Analysis

Secondary data on palm oil production, waste generation, biogas installations, POME treatment compliance rates, and environmental performance indicators were sourced from GAPKI (2018–2023), the Ministry of Environment and Forestry (KLHK) annual reports, the Indonesian National Energy Council (DEN), and peer-reviewed literature. Environmental performance was assessed using GHG emission factors from the IPCC (2021) Tier 2 methodology. Economic performance indicators included waste revenue diversification ratios, capital expenditure recovery periods, and energy cost savings from POME biogas utilization.

CE Adoption Assessment Framework

CE adoption in each case mill was assessed using a structured framework based on the 4R hierarchy (Refuse, Reduce, Reuse, Recycle/Recover) adapted for the agro-industrial context (Ghisellini et al., 2016). Each waste stream was evaluated on a five-point scale across three dimensions: valorization coverage (percentage of waste type addressed), value capture efficiency (proportion of theoretical resource value recovered), and circularity depth (extent to which materials are returned to highest-value applications). A composite CE Adoption Index (CEAI) was calculated for each mill and benchmarked against sectoral best practices documented in the literature.

RESULT AND DISCUSSION

Circular Economy: Theoretical Foundations

The circular economy concept draws on several intellectual traditions, including industrial ecology, cradle-to-cradle design, biomimicry, and the performance economy (Kirchherr et al., 2017). Most broadly, CE is defined as 'an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes' (Kirchherr et al., 2017, p. 224). The Ellen MacArthur Foundation (2013) operationalizes CE through three principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

In industrial ecology, the concept of industrial symbiosis—where the waste or by-product of one industry becomes the raw material for another—is particularly relevant to agro-industrial waste management (Chertow, 2000). Palm oil mills are well suited to industrial symbiosis due to the diversity and volume of their waste streams and the potential to co-locate waste processing facilities with agricultural and energy production systems (Yusoff et al., 2019). The Resource-Based View (RBV) of the firm (Barney, 1991) further suggests that firms that successfully valorize waste streams develop unique capabilities that enhance competitive advantage and long-term sustainability.

Palm Oil Waste Streams and Valorization Potential

The palm oil milling process generates waste at multiple stages. Fresh fruit bunches (FFB) arrive at the mill and undergo sterilization, stripping, digestion, pressing, and clarification processes, each producing distinct waste streams. **Table 1** summarizes the main waste types, estimated quantities, and primary valorization pathways documented in the literature.

Table 1. Palm Oil Waste Streams and Circular Economy Valorization Pathways

Waste Type	Quantity	Environmental Impact	CE Valorization Pathway
POME (liquid)	~60–70% (volume)	BOD/COD loading, CH4 emissions	Biogas (biomethane), bio-fertilizer, biohydrogen
Empty Fruit Bunches (EFB)	~22%	Burning air pollution, leachate	Biocompost, biochar, cellulose/bioethanol, biomass energy
Palm Kernel Shell (PKS)	~5–7%	Landfill pressure if unutilized	Biomass co-firing, activated carbon, biochar
Mesocarp Fiber	~12–13%	GHG if burned openly	Boiler fuel (in-mill), composite boards, bioethanol
Palm Fronds / Trunks	~30–35% at replanting	Open burning, GHG emissions	Mulching, plywood, paper pulp, bioethanol

Waste Type	Quantity	Environmental Impact	CE Valorization Pathway
Decanter Cake	~3–4%	Methane, odor if ponded	Animal feed supplement, organic fertilizer

Source: Adapted from Yusoff et al. (2019); Chiew & Shimada (2013); Sudiyani et al. (2021).

POME is perhaps the most environmentally critical waste stream due to its extremely high biochemical oxygen demand (BOD: 25,000–65,000 mg/L) and chemical oxygen demand (COD: 44,000–102,000 mg/L), which can cause severe water pollution if discharged without treatment (Ahmad et al., 2021). Concurrently, the anaerobic decomposition of POME in open ponds releases methane—a potent GHG with 28 times the global warming potential of CO2 over a 100-year horizon—making POME management a critical target for climate mitigation (IPCC, 2021).

EFB valorization has attracted significant research attention due to its high lignocellulosic content, making it a potential feedstock for bioethanol, biochar, and composting. However, the bulky nature and high moisture content of EFB present logistical challenges for large-scale valorization (Foo & Hameed, 2010). Palm kernel shells, by contrast, have an established market as biomass co-firing fuel and for activated carbon production, and are one of the more commercially advanced CE applications in the sector.

Policy and Regulatory Context in Indonesia

Indonesia's regulatory framework for palm oil waste management has evolved considerably in recent years. Government Regulation No. 101/2014 on Hazardous Waste Management establishes mandatory standards for POME treatment, requiring mills to achieve effluent quality standards before discharge. The Presidential Regulation No. 98/2021 on the National GHG Reduction Action Plan (RAN-GRK) targets a 31.89% unconditional GHG reduction by 2030, with the agriculture and land-use sectors designated as priority mitigation areas (Republic of Indonesia, 2021).

The Mandatory Biogas Programme (MBP), introduced under Ministry of Environment and Forestry Regulation No. P.1/2022, requires palm oil mills with POME pond capacities above 40,000 m^3 to install biogas capture systems. This represents a significant policy lever for accelerating POME valorization, but implementation has been uneven, particularly among smaller and independent mills (Sudiyani et al., 2021). The Indonesian Sustainable Palm Oil (ISPO) certification scheme also incorporates waste management criteria, but civil society organizations and independent evaluators have noted inconsistencies in verification and enforcement (Daemane et al., 2022).

Research Gap and Conceptual Framework

While the technical feasibility of individual palm oil waste valorization technologies is well established, comprehensive assessments of CE adoption across the palm oil value chain in Indonesia—integrating environmental, economic, and governance dimensions—remain scarce (Saswattecha et al., 2015; Geissdoerfer et al., 2017). Furthermore, few studies have applied the CE framework holistically to investigate how mill-level characteristics (scale, ownership type, certification status) interact with policy environments and market conditions to shape CE outcomes. This study fills this gap by adopting a systems perspective on CE adoption in the Indonesian palm oil sector.

The conceptual framework of this study posits that CE adoption in palm oil mills is shaped by three inter-related domains: (1) technological readiness (availability and affordability of valorization technologies); (2) institutional environment (regulatory frameworks, certification schemes, and enforcement); and (3) market and value chain conditions (demand for waste-derived products, access to off-takers, and pricing mechanisms). Together, these domains determine the extent and depth of CE implementation, which in turn drives environmental and economic outcomes at the mill and sector levels.

Current State of CE Adoption in Case Mills

The six case mills exhibited considerable variation in CE adoption levels. Mills A (large multinational-owned) and B (large domestic corporate) achieved the highest CEAI scores (0.74 and 0.68 respectively), largely driven by comprehensive POME biogas capture, EFB composting operations, and integrated PKS biomass energy systems. These mills were both ISPO-certified and subject to the mandatory biogas regulations, highlighting the role of regulatory compliance as a baseline driver of CE adoption.

In contrast, Mills E and F—small cooperative-owned mills—recorded the lowest CEAI scores (0.29 and 0.32), reflecting a predominantly linear waste management approach dominated by open POME ponds and EFB dumping or burning. The medium-sized Mills C and D occupied an intermediate position, with POME biogas capture systems installed but limited EFB valorization beyond land application. These findings suggest a scale and ownership-type gradient in CE adoption that warrants targeted policy attention.

Across all six mills, mesocarp fiber utilization for in-mill boiler fuel was universal, representing the most mature CE application in the sector. POME biogas capture was present in four of six mills (67%), consistent with the industry-wide figure of 68% adoption among large mills reported in the GAPKI (2023) annual survey. However, the utilization of captured biogas varied significantly: Mills A and B employed biogas for electricity generation (achieving energy self-sufficiency of 65–70% of mill electricity demand), while Mill D used biogas only for water heating, capturing a fraction of its potential energy value.

Environmental Performance Outcomes

Comparative analysis of environmental performance data revealed substantive differences between high-CE and low-CE mills. Mills A and B demonstrated GHG emission intensities of 0.38–0.41 tonnes CO2-eq per tonne of CPO produced, compared to 0.67–0.72 for Mills E and F—a reduction of approximately 42–47%. The primary driver of this difference was methane capture from POME; open POME ponds at Mills E and F emitted an estimated 18.4–22.6 kg CH4 per tonne of CPO, contributing disproportionately to their carbon footprint.

Wastewater effluent quality data showed that Mills A and B consistently met or exceeded KLHK discharge standards, with final effluent BOD values of 70–90 mg/L (against the 100 mg/L regulatory limit). Mills E and F frequently exceeded regulatory thresholds (BOD: 145–210 mg/L), indicating systemic non-compliance with environmental regulations. EFB management also differed markedly: Mills A and B composted 85–90% of EFB and sold the resulting compost to smallholder farmers at IDR 350,000–420,000 per tonne, while Mills E and F disposed of EFB through open dumping or incineration, forgoing both environmental and economic benefits.

Table 2. Environmental and Economic Performance of Case Study Mills by CE Adoption Level

Indicator	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
CEAI Score	0.74	0.68	0.55	0.51	0.29	0.32
GHG Intensity (t CO2-eq/t CPO)	0.38	0.41	0.52	0.55	0.67	0.72
Effluent BOD (mg/L)	72	88	108	115	145	210
POME Biogas Capture	Yes	Yes	Yes	Yes	No	No
EFB Valorization (%)	88%	85%	40%	35%	5%	3%
Waste Revenue (% of CPO revenue)	12.4%	10.8%	6.2%	5.1%	0.8%	0.5%

Economic Performance and Value Creation

From an economic perspective, CE-advanced mills demonstrated measurable advantages in revenue diversification and operational resilience. Mills A and B generated waste-derived revenues equivalent to 10.8–12.4% of their CPO revenues, primarily from electricity sales to PLN (national grid) from POME biogas, compost sales, and PKS exports for biomass co-firing. This revenue diversification provided a buffer against CPO price volatility, which remained significant during the 2018–2023 study period (GAPKI, 2023).

The payback period for POME biogas installations was estimated at 4.2–6.8 years across Mills A–D, depending on installed capacity and electricity tariff arrangements. This is consistent with findings by Yusoff et al. (2019) and Ahmad et al. (2021), who reported payback periods of 3–7 years for similar installations in Malaysia and Sumatra. For EFB composting facilities, payback periods were shorter (2.8–4.1 years) due to relatively lower capital costs and strong local demand for organic fertilizer. These figures suggest that, under the right enabling conditions, CE investments in palm oil mills are financially viable and commercially attractive.

Barriers to CE Adoption

Thematic analysis of interview data identified five primary categories of barriers to CE adoption, which were consistent across mills of varying sizes and ownership types. First, capital constraints were identified as the most significant barrier, particularly for small and cooperative mills. The upfront cost of POME biogas capture systems (USD 0.8–2.5 million depending on capacity) and EFB composting facilities (USD 200,000–600,000) represents a prohibitive investment for mills with limited access to credit or grant financing.

Second, technical capacity gaps—including shortages of trained engineers, process operators, and environmental specialists—impeded effective operation and maintenance of waste valorization systems, particularly in smaller mills. Third, market access and off-taker linkages for waste-derived products (compost, biogas-generated electricity, activated carbon) were reported as unreliable or underdeveloped in many areas of Riau, limiting the commercial viability of CE investments. Fourth, fragmented and inconsistently enforced regulatory frameworks—including unclear rules on waste classification, grid connection requirements for biogas electricity, and ISPO certification verification—created uncertainty that deterred investment. Fifth, land and logistics constraints in congested plantation areas limited the deployment of bulky EFB processing infrastructure.

Policy Implications and Recommendations

The findings of this study yield several actionable policy recommendations for Indonesian authorities and industry stakeholders. At the national level, the Government of Indonesia should strengthen and extend the mandatory biogas programme to cover medium-sized mills and establish binding targets for EFB valorization. Green financing mechanisms—including low-interest loans, tax incentives, and public-private investment funds—should be expanded to enable smaller and cooperative mills to invest in CE infrastructure, addressing the capital constraint identified as the primary barrier to adoption.

At the industry level, the Indonesian Palm Oil Association (GAPKI) and the Roundtable on Sustainable Palm Oil (RSPO) should develop standardized CE performance indicators and reporting frameworks, enabling transparent benchmarking and facilitating access to sustainability-linked financing. Investment in technical training and capacity building—particularly for environmental engineers and process operators at small and medium mills—is essential to close the technical capacity gap. Finally, the development of regional waste exchange platforms, where mills can trade or share waste-derived resources (e.g., EFB compost, biogas), could address market access barriers and create economies of scale in CE operations.

CONCLUSION

This study provides comprehensive empirical evidence on the state of circular economy adoption in palm oil waste management in Indonesia, based on mixed-methods analysis of six mills in Riau Province and industry-wide secondary data for 2018–2023. The findings confirm that CE adoption varies significantly across mill types, with large, corporate-owned, and ISPO-certified mills demonstrating substantially higher levels of waste valorization, environmental performance, and economic resilience than smaller, cooperative mills. POME biogas capture has achieved meaningful penetration in the large-mill segment, while EFB and other solid waste valorization remain considerably underdeveloped across the sector.

The environmental benefits of comprehensive CE adoption are substantial, including GHG emission reductions of 42–47% and significant improvements in effluent quality. Economic benefits, including diversified revenue streams and faster payback on CE investments, further support the business case for CE transition in the sector. However, persistent barriers—including capital constraints, technical capacity gaps, fragmented regulatory frameworks, and underdeveloped markets for waste-derived products—continue to inhibit CE uptake, particularly among smaller mills and smallholder producers.

This study contributes to the circular economy literature by providing one of the first comprehensive CE adoption assessments in the Indonesian palm oil sector, grounded in a systems perspective that integrates technological, institutional, and market dimensions. The conceptual framework and CE Adoption Index developed in this study offer transferable tools for assessing CE implementation in other tropical agro-industrial contexts. Methodologically, the mixed-methods design strengthens the rigor and contextual richness of the findings.

Future research should examine the role of digital technologies—including IoT-based waste monitoring, blockchain for supply chain transparency, and artificial intelligence for process optimization—in enabling CE transitions in palm oil mills. Longitudinal studies tracking CE adoption trajectories over time would further illuminate the dynamic relationships between policy interventions, investment decisions, and environmental outcomes. Additionally, research extending to smallholder palm oil producers—who account for approximately 40% of Indonesia's total palm oil area but remain largely excluded from existing CE frameworks—is urgently needed to ensure an inclusive and equitable CE transition.

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