Industrial and Domestic Waste Management

Review
Volume 6(2), 2026, 546−566
https://doi.org/10.53623/idwm.v6i2.1448

Transforming Palm Oil Mill Wastewater into Environmental and Economic Value through Management Accounting and Environmental Management System

Andifa Khalida Azzara, Dwi Nowo Martono*, Djoko Mulyo Hartono

Departement Environmental Science, School of Environmental Science, Universitas Indonesia, Jakarta 10430, Indonesia

*Correspondence: nowo2003@yahoo.com

SUBMITTED: 1 October 2026; REVISED: 14 October 2026; ACCEPTED: 20 October 2026

ABSTRACT: Palm oil mill effluent (POME) poses significant environmental challenges due to its high organic load, substantial generation volume, and potential methane emissions. Despite advances in wastewater treatment and resource recovery, limited integration with environmental management accounting and environmental management systems restricts opportunities for environmental and economic value creation. This review aims to evaluate the integration of wastewater treatment technologies, resource recovery, environmental management accounting, and ISO 14001-based environmental management systems for sustainable POME management. A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Of 126 identified records, 18 duplicates were removed, 45 records were excluded during screening, and 63 peer-reviewed articles were included in the synthesis. The findings reveal a transition from conventional wastewater treatment toward anaerobic digestion, renewable energy recovery, circular economy practices, and waste valorization. However, significant gaps remain in integrating engineering-based resource recovery with environmental cost assessment, material flow analysis, and ISO 14001 implementation. An integrated framework is proposed that combines physical and monetary environmental accounting, material flow cost accounting, and the Plan-Do-Check-Act cycle with resource recovery and sustainability governance. The framework emphasizes evaluating avoided treatment costs, material savings, energy substitution, greenhouse gas emission reductions, and environmental performance within a unified decision-making system. This review concludes that integrating technological, accounting, and environmental management approaches offers a pathway for transforming POME management from pollution control into environmental and economic value creation. Future research should validate the framework through mill-level empirical studies and standardized sustainability indicators.

KEYWORDS: Wastewater; resource recovery; eco-efficiency; waste valorization; sustainability

1. Introduction

The palm oil industry plays a significant economic role in major producing countries, particularly Indonesia and Malaysia. However, its continued expansion also generates substantial environmental pressures. One of the most persistent challenges is palm oil mill effluent (POME), a hot, acidic wastewater stream generated during sterilization, clarification, hydrocyclone operations, and kernel separation. POME contains high concentrations of biodegradable organic matter, suspended solids, oil and grease, and nutrients. Untreated or inadequately managed POME can deplete dissolved oxygen in receiving waters, contaminate soil and aquatic environments, and contribute to methane emissions through anaerobic decomposition [1–4]. These environmental concerns have traditionally positioned POME management primarily as a pollution-control activity, emphasizing wastewater treatment and regulatory compliance rather than resource efficiency and economic value creation.

Over the past two decades, research has increasingly shifted toward recognizing POME as a potential resource rather than merely an environmental liability. Anaerobic digestion can simultaneously reduce organic loading and generate biogas, while alternative treatment and recovery technologies offer opportunities for biohydrogen production, nutrient recovery, fertilizer generation, and renewable energy production [1, 5–8]. This transition aligns with circular economy principles, which emphasize retaining, recovering, and regenerating resources rather than disposing of residual materials [3, 5]. For palm oil mills, these developments offer opportunities to transform wastewater management from a cost-intensive environmental obligation into a system capable of generating energy savings, recovering valuable materials, reducing emissions, and creating additional economic benefits. Nevertheless, realizing these benefits requires more than technological improvements, as resource recovery must also be supported by appropriate accounting mechanisms and organizational management systems.

Environmental Management Accounting (EMA) provides a mechanism for integrating physical information on material consumption, energy use, water utilization, waste generation, and emissions with monetary information on environmental costs and benefits [9, 10]. Physical Environmental Management Accounting (PEMA) enables organizations to identify and monitor material flows, resource consumption, and process losses, whereas Monetary Environmental Management Accounting (MEMA) supports the assessment of treatment expenditures, environmental investments, avoided costs, and economic returns. Material Flow Cost Accounting (MFCA) further strengthens this approach by identifying the monetary value of material losses that conventional accounting systems may classify as overhead expenses or general waste-management costs [11–15]. In the context of POME management, these accounting approaches can translate technical indicators, such as organic load reduction, biogas generation, and nutrient recovery, into measurable environmental and economic information. Such integration is essential for supporting investment decisions, evaluating resource recovery performance, and identifying opportunities for operational improvement.

ISO 14001-based environmental management systems provide a complementary organizational framework for integrating environmental objectives with operational practices and management decisions. Through the Plan-Do-Check-Act (PDCA) cycle, ISO 14001 establishes a systematic approach to identifying environmental aspects, setting objectives, implementing operational controls, monitoring performance, and promoting continual improvement [16–19]. Within palm oil mills, this framework can support the integration of

wastewater reduction targets, resource recovery strategies, emissions monitoring, environmental performance indicators, and corrective actions into routine management processes. When combined with EMA, ISO 14001 has the potential to connect environmental compliance, resource efficiency, and economic performance within a coordinated decision-making framework. However, the practical integration of these approaches in POME management remains insufficiently explored.

Despite substantial advances in wastewater treatment, resource recovery, environmental accounting, and environmental management systems, the existing literature remains fragmented. Engineering studies predominantly emphasize pollutant removal efficiency, reactor performance, methane recovery, and technological optimization, with limited consideration of environmental costs, material losses, and economic decision-making. Conversely, EMA research generally focuses on environmental cost identification, resource accounting, and sustainability reporting at the organizational level, with relatively limited application to specific high-impact wastewater streams. Similarly, studies examining ISO 14001 implementation frequently emphasize regulatory compliance, environmental performance, and organizational practices without explicitly connecting environmental management systems to waste valorization and environmental accounting [11, 15, 17–19]. Consequently, a significant research gap exists between the technical potential of POME resource recovery, the economic recognition of recovered resources, and the organizational mechanisms required to translate these benefits into measurable environmental and financial performance.

The novelty of this review lies in proposing an integrated operational framework that connects POME treatment and resource recovery with environmental management accounting, MFCA, and ISO 14001-based environmental governance. Unlike conventional circular economy frameworks, which primarily emphasize resource circulation and waste valorization, the proposed approach explicitly links physical resource flows, monetary valuation, and organizational decision-making [3, 5]. Specifically, wastewater treatment and resource recovery outputs are incorporated into physical environmental accounting records, while associated material losses, avoided expenditures, and recovered resource values are quantified through monetary environmental accounting and MFCA. These indicators are subsequently integrated into the ISO 14001 PDCA cycle to support environmental objectives, operational controls, performance evaluation, corrective actions, and management reviews. This integrated approach provides a conceptual basis for examining whether coordinated technological, accounting, and governance practices can improve environmental outcomes and economic performance compared with conventional approaches that manage these functions separately. Its contribution is therefore the development of a structured decision-making framework rather than the introduction of a new wastewater treatment technology.

Accordingly, this review aims to critically evaluate the integration of POME treatment technologies, resource recovery strategies, environmental management accounting, and ISO 14001-based environmental management systems to support environmental sustainability and economic value creation in the palm oil industry. Specifically, the review examines the transition from conventional pollution control toward resource recovery, evaluates the potential of EMA and MFCA to quantify the physical and monetary benefits of POME management, and investigates how ISO 14001 can provide the governance structure necessary to institutionalize these benefits within organizational decision-making. Through a systematic

synthesis of the existing literature, the study identifies major research gaps, develops an integrated waste-to-value management framework, and proposes directions for future empirical validation. The findings are expected to provide a conceptual foundation for integrating technological performance, environmental cost management, resource efficiency, and sustainability governance in palm oil mills.

2. Materials and Methods

2.1. Review Design and Information Sources.

This study is a qualitative systematic literature review with thematic synthesis. The source manuscript names Google Scholar, ScienceDirect, Scopus, SpringerLink, and a Mendeley library and lists POME, environmental management accounting, ISO 14001, circular economy, waste valorization, waste-to-energy, and sustainability as search concepts. It does not, however, provide executed database-level search histories, dates, record yields, or an unambiguous publication-year cutoff. The search strings in Table 1 are therefore a reproducibility template proposed during revision, NOT a record of searches verified as executed. Authors must reconcile them with the original search exports before asserting that the review is fully reproducible [20].

The earlier draft referred to a recent five-year emphasis while citing foundational studies from before that period. For a potential refreshed search, 2020–2026 is proposed for recent empirical literature, with pre-2020 works retained separately as foundational theory when directly relevant. This proposed range must not be presented as the historical eligibility rule without source-log confirmation. Last search date: not documented in the supplied materials; author confirmation required. Database-specific record counts: not documented.

Table 1. Database-Specific Search Protocol Proposed For Verification (Not A Record Of Historical Execution).

Source	Candidate reproducible query or approach	Limit / reporting status
Scopus	TITLE-ABS-KEY(("palm oil mill effluent" OR POME) AND ("environmental management accounting" OR "material flow cost accounting" OR "ISO 14001" OR "circular economy" OR "resource recovery" OR "waste valorization" OR biogas))	Proposed years: 2020–2026; exact run date and number of hits unverified
ScienceDirect	("palm oil mill effluent" OR POME) AND ("resource recovery" OR biogas OR "environmental management accounting" OR "ISO 14001" OR "circular economy")	Use platform search fields and article/year filters; historical filter undocumented
SpringerLink	"palm oil mill effluent" AND (biogas OR "resource recovery" OR "ISO 14001" OR "environmental accounting")	Search terms adapted to website syntax; historical run undocumented
Google Scholar	"palm oil mill effluent" ("resource recovery" OR biogas OR "circular economy"); separate searches for "environmental management accounting" "palm oil" and "ISO 14001" "palm oil"	Document dates, page depth, and duplicates; original search history unavailable
Mendeley Library	Screen imported records by title, DOI, journal and relevance; use as reference-management/supplemental source, not as a directly reproducible bibliographic database	Export imported records and source provenance; historic retrieval counts unavailable

2.2. Eligibility, Screening, and Synthesis.

The source manuscript screened records for relevance to POME management, EMA/MFCA, ISO 14001/environmental management systems, circular economy, waste valorization,

resource recovery, or sustainability. It excluded duplicates, non-academic opinion, unavailable full texts, and records outside the conceptual scope. The reported flow is 126 identified records, 18 duplicates removed, 108 screened, 45 excluded during screening, and 63 retained for synthesis. The original material does not document retrieval failure counts, reasons for full-text exclusions, individual screening decisions, or whether screening was conducted independently by multiple reviewers. These missing details should be supplied from the review audit trail rather than guessed [20].

Table 2. Identification and Selection of Literature In The Source Systematic Review.

Stage	Description	Records (n)
Initial search	Records identified across Google Scholar, ScienceDirect, Scopus, SpringerLink, and Mendeley Library.	126
Duplicates removed	Duplicate records identified through titles and metadata were removed.	18
Title, abstract, and keyword screening	Records remaining after duplicate removal were screened for topical relevance.	108
Excluded after screening	Records outside the scope of POME, EMA, ISO 14001, circular economy, or sustainability were excluded.	45
Full-text assessment	Full-text articles assessed for conceptual and methodological relevance.	38
Included in synthesis	Peer-reviewed articles included in the final systematic review.	38

For methodological transparency, a future appraisal should evaluate conceptual and practical usefulness according to five dimensions: (i) direct relevance to POME or to transferable EMA/ISO 14001 mechanisms; (ii) clarity of design and context; (iii) transparency of methods and assumptions; (iv) appropriateness of physical, financial, or governance measures; and (v) reporting of uncertainty and limitations. A future auditable appraisal can grade each dimension 0 (not reported), 1 (partially reported), or 2 (adequately reported), using two assessors and an agreed resolution process. Because no historical study-by-study appraisal matrix was supplied, the review does not claim that this rubric was retrospectively applied to all 38 records.

The literature identification and selection process is illustrated in Figure 1, which presents a PRISMA 2020-oriented flow diagram reconstructed from the numerical records reported in the original manuscript. The thematic synthesis organizes the literature into five primary categories: POME treatment, circular economy and waste valorization, Environmental Management Accounting (EMA), ISO 14001 and Environmental Management Systems (EMS), and sustainability transformation. Each publication is assigned to a primary category based on its dominant research objective or contribution, while secondary and cross-cutting themes are documented narratively. For methodological reproducibility, future data extraction should systematically record bibliographic information, geographical location, research design, treatment technologies or governance mechanisms, quantitative performance indicators, principal findings, study limitations, and thematic classifications. However, because the original publication-level dataset and extraction records were unavailable, the thematic proportions presented in subsequent sections reflect the classifications reported in the source manuscript rather than an independently verified reclassification. Furthermore, the VOSviewer visualizations are interpreted descriptively to identify research patterns and thematic relationships and should not be considered evidence of causal associations.

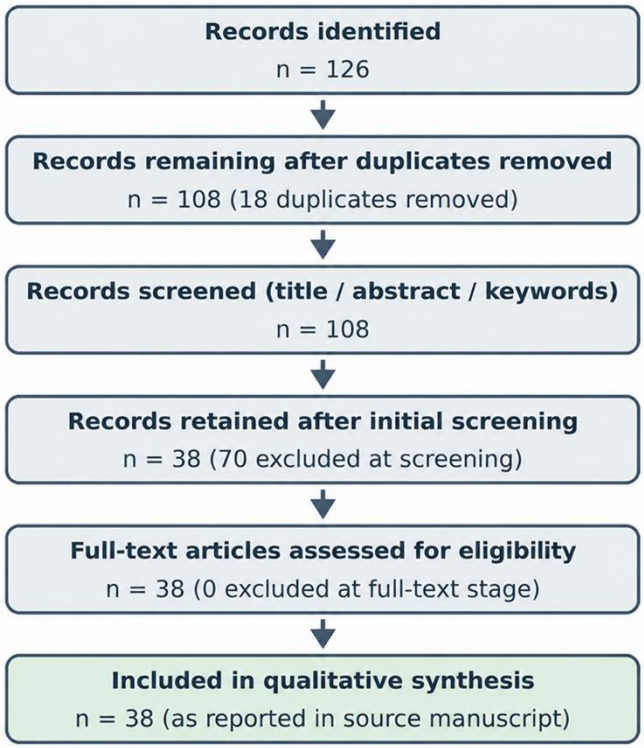


Figure 1. PRISMA 2020-Oriented Selection Flow Reconstructed From the Five Numerical Counts Reported in the Source Draft.

3. Results and Discussion

3.1. Evolution of the Evidence Base.

The reviewed literature demonstrates varying levels of research attention across five major thematic areas. As illustrated in Figure 2, POME treatment accounts for 28% of the reviewed publications, followed by circular economy and waste valorization (25%), Environmental Management Accounting (EMA) (21%), ISO 14001 and Environmental Management Systems (EMS) (13%), and sustainability transformation (13%). These percentages represent the rounded proportions reported in the original thematic classification, as the underlying publication-level allocation was unavailable for independent verification. Collectively, POME treatment and circular economy applications account for 53% of the reviewed literature, indicating a stronger research emphasis on technological feasibility and resource recovery than on the integration of recovered resources into environmental accounting and managerial decision-making.

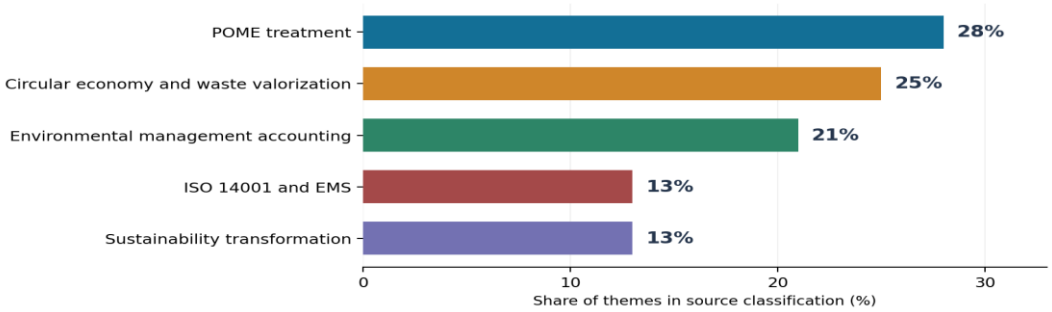


Figure 2. matic shares (%) reproduced from the original review classification

In contrast, the relatively smaller proportion of EMA-related studies (21%) highlights the need for further investigation into the economic valuation of recovered resources, environmental cost allocation, and financial performance assessment. Nevertheless, these percentages describe the thematic distribution of the reviewed publications and should not be interpreted as indicators of research quality or methodological rigor. Malaysia and Indonesia experience similar environmental challenges associated with POME generation and management, although the reviewed literature reveals differences in research emphasis and institutional approaches. Studies focusing on Malaysia frequently examine wastewater treatment technologies, anaerobic digestion, membrane-based recovery, and process optimization to improve treatment efficiency and resource utilization [2, 21]. In contrast, Indonesian studies increasingly address POME valorization within circular economy frameworks, Indonesian Sustainable Palm Oil (ISPO) certification, sustainability governance, and emerging opportunities for biogas and bio-compressed natural gas (bio-CNG) production [8, 22–25]. These distinctions reflect the thematic characteristics of the cited publications rather than a comprehensive quantitative comparison between the two countries. Furthermore, ISPO certification and ISO 14001 represent different sustainability governance mechanisms and should not be considered interchangeable. Variations in environmental monitoring infrastructure, financial resources, regulatory enforcement, energy markets, and site-specific operating conditions may influence the technical and economic feasibility of different POME treatment and resource recovery strategies.

The geographical distribution of the reviewed literature, presented in Figure 3, further highlights the contributions of major palm oil-producing countries, particularly Malaysia and Indonesia. Malaysian research frequently emphasizes anaerobic digestion, bioenergy recovery, wastewater treatment performance, and technological optimization, whereas Indonesian publications increasingly explore the relationships among palm oil production, environmental governance, sustainability practices, and emerging environmental accounting approaches. Meanwhile, studies conducted outside the major palm oil-producing regions contribute broader conceptual and methodological perspectives on EMA, circular economy principles, sustainability accounting, and environmental management systems. These international contributions provide complementary theoretical foundations for developing integrated POME management strategies. However, because the original publication-level geographical dataset was unavailable, these observations should be interpreted as descriptive patterns rather than statistically verified differences in national research contributions.

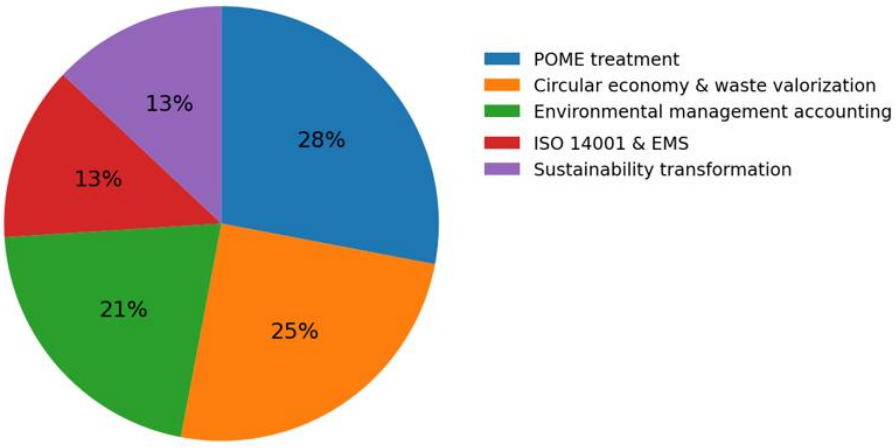


Figure 3. Thematic Distribution Reported in the Source Review Corpus.

3.2. From Wastewater Treatment To Resource Recovery.

Palm oil mill effluent (POME) treatment remains a fundamental component of the existing research literature, primarily because of its high concentrations of biodegradable organic matter, suspended solids, and oil and grease. As summarized in Table 3, POME typically exhibits elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), along with acidic conditions that influence treatment selection and operational performance. Consequently, conventional treatment approaches have focused on anaerobic digestion, biological treatment, membrane filtration, adsorption, coagulation–flocculation, and integrated wastewater treatment systems [1, 2, 26]. Among these technologies, anaerobic digestion has received particular attention because it simultaneously reduces organic pollution and generates methane-rich biogas. This dual function establishes anaerobic digestion as an important technological pathway connecting conventional pollution control with renewable energy recovery and resource utilization.

Table 3. General Characteristics of Palm Oil Mill Effluent Reported in the Source Draft.

Parameter	Typical range	Implications for choice of technology	Supporting literature
Biochemical oxygen demand	25,000-35,000 mg/L	High biodegradable load supports anaerobic treatment; monitor load stability and residual BOD.	[1, 2, 25, 27, 28]
Chemical oxygen demand	50,000-70,000 mg/L	Anaerobic digestion may recover energy; refractory residual COD may require polishing.	[1, 2, 25, 27, 28]
pH	4-5	Acidity can require equalization/alkalinity control for stable methanogenesis.	[2, 25, 27]
Total suspended solids	15,000-25,000 mg/L	Screening, settling and solids handling can reduce clogging or membrane fouling.	[2, 21, 25, 28]
Oil and grease	2,000-7,000 mg/L	Upstream oil removal and fat management may reduce inhibition/fouling.	[2, 21, 25, 28]

Anaerobic digestion converts biodegradable organic compounds in POME into methane-rich biogas through a series of microbial processes while simultaneously reducing the wastewater's organic load. However, effective energy recovery requires more than methane generation alone. Gas-tight collection systems, methane leakage prevention, hydrogen sulfide removal, and appropriate biogas utilization technologies are essential for achieving meaningful environmental and economic benefits. Treatment performance is influenced by several operational parameters, including organic loading rate, hydraulic retention time, pH, temperature, microbial inoculum, and process stability. Co-digestion with other palm oil processing residues may further enhance methane recovery under suitable operating conditions, although it can introduce additional variability in feedstock composition and complicate material flow accounting [6, 26, 29]. Importantly, the environmental benefits of anaerobic digestion depend on the actual capture and utilization of methane rather than theoretical biogas production potential. Therefore, reliable assessments should incorporate measured methane recovery, energy substitution, operational losses, and associated greenhouse gas emissions.

Nutrient recovery represents another important pathway for transforming POME into valuable resources. Digestate and downstream treatment residuals may retain nitrogen,

phosphorus, potassium, and organic matter that could potentially be recovered for agricultural applications [30]. However, their suitability for fertilizer production depends on nutrient composition, product quality, pathogen and contaminant control, agronomic requirements, and compliance with applicable environmental standards. Similarly, membrane-based technologies offer opportunities for water reclamation, resource separation, and biogas upgrading, but their implementation must account for membrane fouling, pretreatment requirements, concentrate management, chemical cleaning, and operational expenditures [21]. These technical and economic considerations demonstrate that circular resource recovery cannot be evaluated solely through pollutant removal efficiency. Instead, a credible waste-to-value strategy requires measurable recovered products, technically feasible utilization pathways, quantified environmental burdens, and an assessment of associated economic costs and benefits. Integrating these indicators into environmental management accounting would provide a more comprehensive basis for evaluating the sustainability and economic feasibility of POME resource recovery.

3.3. Environmental Management Accounting and Economic Valuation.

Environmental Management Accounting (EMA) provides a conceptual framework for translating POME-related material and energy flows into information that supports environmental and economic decision-making. Physical Environmental Management Accounting (PEMA) systematically records the quantities of water, energy, raw materials, products, waste, and emissions associated with industrial operations. In contrast, Monetary Environmental Management Accounting (MEMA) assigns monetary values to these physical flows by identifying operational expenditures, cost savings, environmental investments, potential liabilities, and economic benefits [9–12]. Material Flow Cost Accounting (MFCA) further strengthens this integration by allocating costs to both valuable products and material losses, thereby identifying resource inefficiencies that conventional accounting systems may overlook or classify as general overhead and waste-management expenses [13–15]. Together, these approaches provide a structured basis for evaluating resource efficiency, environmental costs, and the economic implications of waste recovery.

In the context of POME management, physical environmental accounting can quantify wastewater generation, organic pollutant loads, methane capture, renewable energy production, nutrient recovery, water reuse, and residual waste generation. These physical indicators can subsequently be integrated into monetary environmental accounting to evaluate wastewater treatment expenditures, avoided energy purchases, fertilizer substitution benefits, reduced waste disposal costs, potential carbon-related revenues or savings, and capital investments in resource recovery technologies. Integrating physical and monetary information enables the development of eco-efficiency indicators that relate environmental improvements to economic performance. Such indicators can support comparisons among treatment alternatives, identify opportunities for resource optimization, and provide quantitative evidence for investment decisions. Furthermore, incorporating MFCA can improve the identification of material losses throughout POME treatment and recovery processes, allowing palm oil mills to assess the economic consequences of inefficient resource utilization and prioritize interventions that deliver both environmental and financial benefits [9–15].

Despite these potential advantages, the review indicates that the practical application of EMA and MFCA in POME management remains insufficiently developed. Existing EMA

research suggests that environmental cost information can strengthen strategic decision-making, improve resource allocation, and support sustainability management. However, much of the available literature remains conceptual, cross-sectoral, or focused on organization-wide environmental performance rather than specific wastewater treatment processes [11, 12, 31]. Conversely, POME-related engineering studies frequently provide detailed information on treatment efficiency, pollutant removal, biogas production, and resource recovery but rarely integrate these physical measurements into systematic environmental accounting frameworks. This disconnect represents a significant research gap because it limits the ability of palm oil mills to compare treatment and recovery alternatives based on their combined environmental and economic consequences. Addressing this gap requires the development and empirical validation of integrated accounting approaches that connect measurable treatment performance with material flow costs, environmental expenditures, resource recovery benefits, and long-term sustainability outcomes.

3.4. ISO 14001 as a Governance Architecture.

ISO 14001 provides a structured environmental management framework that can institutionalize POME-related sustainability objectives within palm oil mill operations. Through the Plan-Do-Check-Act (PDCA) cycle, the standard establishes a systematic approach to environmental planning, operational implementation, performance evaluation, and continual improvement. During the Plan phase, palm oil mills identify significant environmental aspects, applicable legal and other requirements, environmental risks and opportunities, and measurable performance objectives. For POME management, these objectives may include reducing wastewater generation, improving methane capture efficiency, increasing renewable energy recovery, enhancing nutrient recycling, minimizing greenhouse gas emissions, and improving material efficiency [16–18]. Integrating these objectives into environmental management systems can help align wastewater treatment and resource recovery activities with broader organizational sustainability strategies.

The Do phase translates environmental objectives into operational practices through the allocation of responsibilities, personnel training, competence development, documentation, and implementation of appropriate treatment and resource recovery technologies. Subsequently, the Check phase evaluates environmental performance through systematic monitoring, measurement, compliance evaluation, and internal audits, with the results informing management review. Integrating Environmental Management Accounting (EMA) into this phase can strengthen performance evaluation by incorporating physical resource flows, environmental expenditures, avoided costs, and resource recovery benefits alongside conventional environmental indicators. Finally, the Act phase uses monitoring results, audit findings, and management review outcomes to identify corrective actions and opportunities for continual improvement. This integrated process establishes a connection between environmental governance, operational efficiency, and economic decision-making, enabling palm oil mills to evaluate sustainability performance beyond regulatory compliance [16–19].

The relationships among environmental management, resource recovery, and sustainability-related research themes are illustrated in Figure 4. The network visualization represents the thematic connections identified in the source bibliometric analysis, providing an overview of how different research areas are associated within the reviewed literature. However, the visualization should not be interpreted as evidence of direct causal relationships

or successful operational integration. Previous studies have associated environmental management systems with improved environmental performance, cleaner production practices, resource efficiency, organizational accountability, and sustainability governance [17–19, 32].

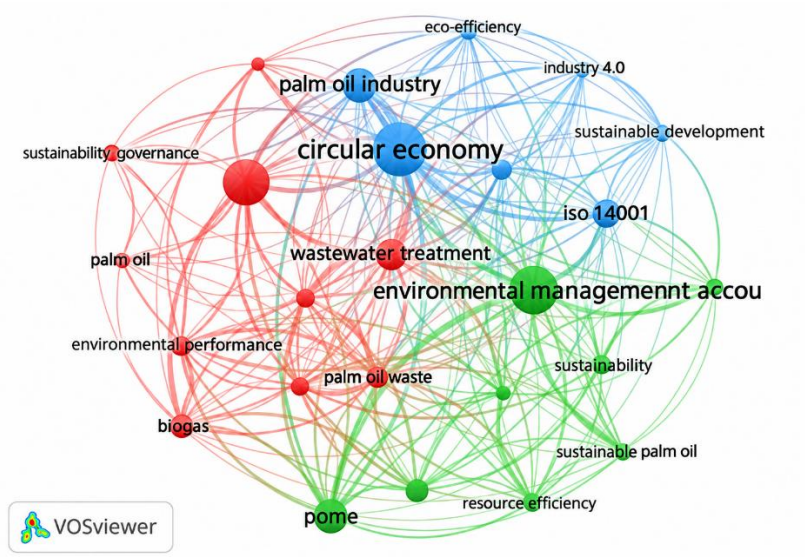


Figure 4. Network Visualization of Themes in The Source Bibliometric Analysis.

The temporal development of research themes is presented in Figure 5 through an overlay visualization. This approach provides an additional perspective on the evolution of research interests by distinguishing themes according to their temporal characteristics. In the context of POME management, the visualization can help examine how conventional wastewater treatment research relates to broader discussions of resource recovery, circular economy practices, environmental accounting, and sustainability governance. Accordingly, the figure should be interpreted as a descriptive representation of thematic development rather than definitive evidence of a chronological transition between research approaches. Studies addressing sustainability certification and environmental governance in the palm oil sector also emphasize the importance of traceability, transparency, and measurable environmental performance [22, 33–35]

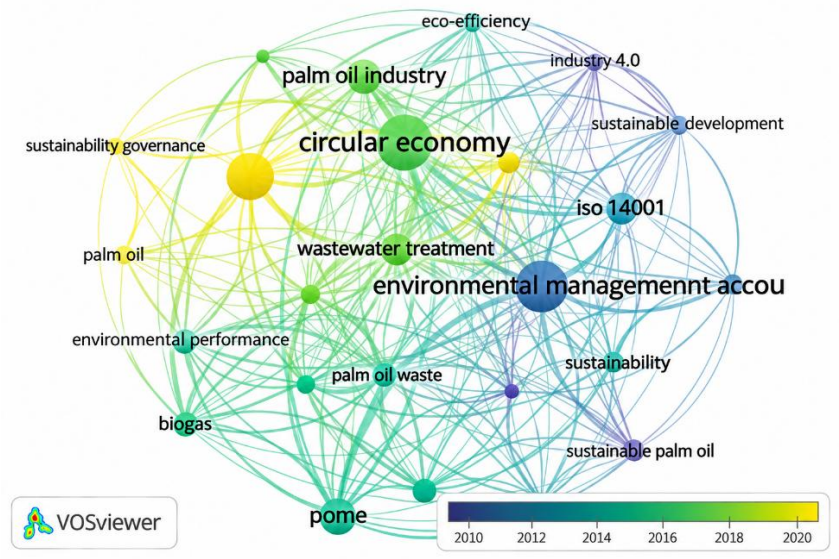


Figure 5. Overlay Visualization Showing the Temporal Development of Themes in the Source Bibliometric Analysis.

The concentration of research themes is further illustrated in Figure 6, which presents the density visualization generated from the source bibliometric analysis. This visualization provides a complementary perspective by highlighting areas with relatively greater concentrations of bibliometric items and their associated relationships, depending on the visualization settings. Such patterns can help identify established research concentrations and comparatively less-developed thematic connections. However, higher density does not necessarily indicate greater scientific quality, practical importance, or evidence of successful implementation. Although environmental management systems have been associated with improvements in environmental performance and sustainability governance, direct empirical investigations connecting ISO 14001 implementation, POME resource recovery, and EMA-based economic outcomes remain limited [17–19, 32]. This gap highlights the need for integrated mill-level studies that evaluate how environmental management practices influence measurable resource recovery performance, environmental costs, and economic benefits.

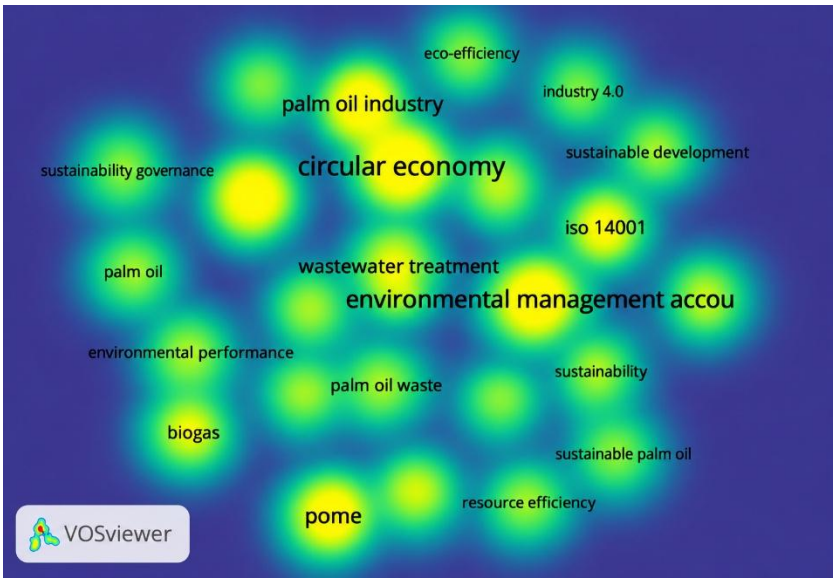


Figure 6. Density Visualization of Themes in the Source Bibliometric Analysis.

3.5. Integrative Framework

The reviewed literature suggests that POME management, Environmental Management Accounting (EMA), ISO 14001, circular economy principles, and sustainability governance can be integrated into a complementary management framework rather than treated as independent research areas. POME management addresses wastewater generation, pollutant loading, and associated environmental risks, while treatment and resource recovery technologies determine the potential for pollutant reduction, energy generation, and material recovery. EMA translates these physical flows into measurable environmental and monetary information, enabling organizations to evaluate resource efficiency, environmental expenditures, and economic benefits. Meanwhile, ISO 14001 provides a structured governance mechanism through which environmental objectives, operational controls, performance monitoring, and continual improvement can be institutionalized. Circular economy principles establish the strategic direction for retaining and recovering resource value, while sustainability governance connects operational performance with organizational accountability and long-term decision-making. Collectively, these components provide a conceptual foundation for

integrating technological performance, environmental accounting, and sustainability management.

The proposed integration is illustrated in Figure 7, which presents the conceptual relationships among POME treatment, resource recovery, EMA, Material Flow Cost Accounting (MFCA), and ISO 14001-based environmental management systems. The framework establishes a sequential but iterative process in which wastewater treatment and resource recovery generate measurable physical outputs, including reduced pollutant loads, captured methane, recovered nutrients, and reusable water. Physical EMA subsequently records material, energy, water, waste, and emission flows, while Monetary EMA and MFCA assign economic values to recovered resources, avoided expenditures, and material losses within consistent system boundaries. These environmental and economic indicators are then incorporated into the ISO 14001 Plan-Do-Check-Act (PDCA) cycle to support objective setting, operational implementation, performance evaluation, corrective actions, and continual improvement. Importantly, environmental improvements and economic benefits should initially be evaluated separately before being integrated into a comprehensive sustainability assessment. The proposed framework represents a conceptual synthesis of the reviewed literature rather than an empirically validated management system.

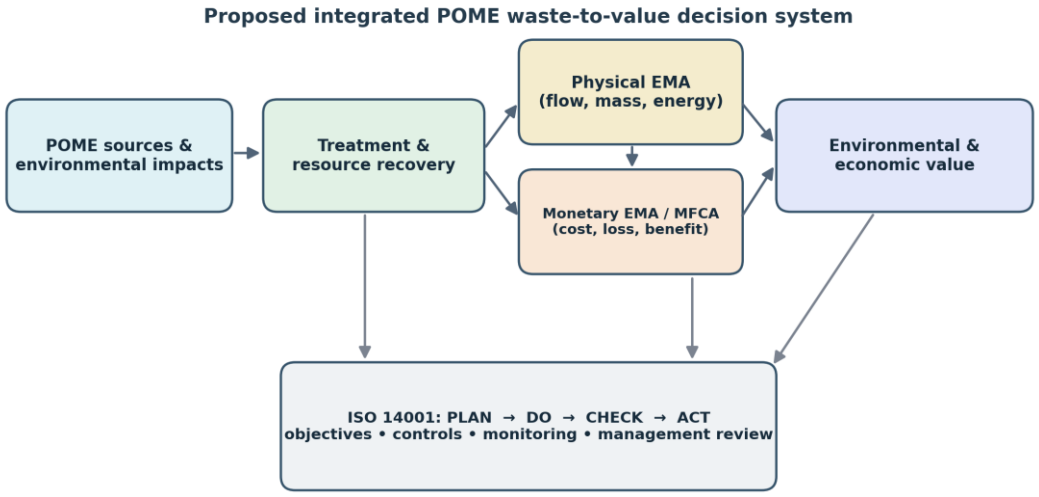


Figure 7. Proposed Conceptual Integration of POME Treatment, Recovery, EMA/MFCA And ISO 14001 Toward Environmental and Economic Value.

The operational components, expected management outcomes, and illustrative key performance indicators (KPIs) associated with the proposed framework are summarized in Table 4. The framework comprises six interconnected components: POME management, resource recovery, Physical EMA, Monetary EMA, MFCA, and ISO 14001. Each component contributes a distinct analytical function, ranging from quantifying wastewater generation and treatment performance to evaluating resource recovery, environmental costs, material losses, and organizational improvement. The proposed indicators provide a basis for monitoring environmental and economic performance at the palm oil mill level. However, these indicators are intended as examples for future empirical application and validation rather than measured outcomes derived from the 38 publications included in the review.

Table 4. Proposed Integrative Framework for POME Environmental and Economic Value Creation.

Component	Primary analytical focus	Expected management outcome	Illustrative measurable KPI
POME management	Waste generation, organic load, emissions, treatment performance	Reduced environmental risk	m³ POME/t FFB; kg COD removed; effluent compliance rate
Resource recovery	Methane, energy, nutrients and water recovery	Substitute resources and limit emissions	Nm³ CH_4 captured; kWh/t FFB; kg nutrients recovered
Physical EMA	Material, water, energy, waste, nutrient and emission flows	Resource-efficiency information	Input-output reconciliation (%); meter coverage (%)
Monetary EMA	Treatment cost, environmental expenditure, avoided cost, recovered value	Economic decision information	Treatment cost/m³; avoided energy cost; net benefit/period
Material Flow Cost Accounting	Material losses and cost of non-product output	Identification of hidden inefficiency	Non-product output cost/t FFB; loss-cost reduction (%)
ISO 14001	Plan-Do-Check-Act, compliance, objectives, controls and review	Governed continual improvement	KPI attainment (%); overdue corrective actions; audit closure days

4. Discussion

4.1. Balancing Environmental Benefits with Economic Constraints.

The reviewed literature demonstrates that POME management has evolved beyond conventional wastewater treatment toward resource recovery and integrated sustainability management. However, the transition toward a comprehensive environmental and economic management framework remains incomplete. Previous studies have established technically feasible approaches for reducing organic pollution, recovering renewable energy, and extracting valuable nutrients from POME [1, 2, 5–8, 23, 26]. Circular economy research provides a strategic foundation for transforming residual waste streams into recoverable resources and promoting resource efficiency within industrial production systems [3, 5, 24, 36, 37]. Meanwhile, Environmental Management Accounting (EMA) offers a systematic approach to quantifying physical resource flows and their monetary implications [9–15, 31], while ISO 14001 provides an organizational framework for environmental performance monitoring, operational control, and continual improvement [16–19]. Despite these complementary contributions, empirical investigations integrating technological performance, environmental accounting, and sustainability governance within a single palm oil mill remain limited.

This fragmentation creates practical challenges because each research discipline addresses different aspects of environmental and economic management. Engineering studies can quantify methane production, pollutant removal, and energy recovery but may not establish whether the recovered resources generate measurable cost savings, additional revenue, or long-term investment benefits. Conversely, accounting approaches can identify environmental expenditures and financial performance but may fail to capture the physical sources of resource losses without reliable process-level measurements. Environmental management systems can establish objectives, operational procedures, and monitoring requirements, yet compliance-oriented indicators alone may not adequately reflect the economic value of recovered materials and energy. Consequently, integrating technological, accounting, and governance information

is essential for supporting consistent investment decisions, resource allocation, and sustainability performance evaluation [9–15, 17–19].

The economic value of POME valorization should nevertheless be evaluated carefully because resource recovery does not automatically generate positive net financial returns. Anaerobic digestion, advanced wastewater treatment, membrane separation, monitoring infrastructure, and resource recovery technologies require capital investment, operational expenditure, maintenance, technical expertise, and reliable process management. Therefore, the economic feasibility of a particular recovery pathway depends not only on the quantity of recovered resources but also on its overall environmental and financial performance under site-specific operating conditions. EMA, MFCA, and life-cycle-oriented assessment approaches can provide a more comprehensive evaluation by incorporating investment costs, operational expenses, material losses, avoided resource purchases, residual treatment requirements, and potential environmental trade-offs [13–15, 38]. Such assessments are necessary to distinguish technically feasible recovery systems from economically and environmentally sustainable alternatives.

Comparisons among POME treatment and recovery pathways further demonstrate the importance of evaluating waste-to-value strategies within clearly defined system boundaries. Anaerobic digestion can reduce organic loading while generating methane-rich biogas, but its environmental and economic benefits may be reduced by high initial investment costs, methane leakage, process instability, and inadequate gas utilization infrastructure. Membrane-based polishing and biogas upgrading technologies can improve recovered water or gas quality, although membrane replacement, chemical cleaning, pretreatment, and concentrate management may increase operational expenditures [21, 25]. Similarly, nutrient recovery offers opportunities to substitute purchased fertilizers, but its feasibility depends on recovered product quality, regulatory requirements, and reliable market demand [27, 29, 38]. Conventional lagoon-based systems may involve lower initial investment costs but generally provide fewer opportunities for controlled resource recovery and may generate unmanaged methane emissions. Accordingly, robust technology selection requires consistent assessment boundaries, life-cycle costs, operational reliability, and verified environmental performance rather than comparisons based exclusively on maximum recovery potential. These observations represent qualitative interpretations of the reviewed literature rather than an empirically established ranking of treatment technologies.

4.2. Why Environmental Management Accounting Is the Missing Bridge.

Environmental Management Accounting represents a central component of the proposed integrative framework because it connects physical resource recovery with measurable economic and managerial value. POME contains identifiable material and energy flows, including wastewater, organic carbon, nutrients, oil residues, methane, recovered energy, and residual solids. These components can initially be quantified through physical environmental accounting before their associated financial implications are evaluated. A systematic accounting approach should therefore begin with reliable mass and energy balances, establish clear operational responsibilities and cost centers, and subsequently translate physical measurements into monetary information. Integrating these processes can support more transparent assessments of treatment efficiency, resource recovery, environmental expenditures, and economic performance [9–15, 31].

The application of EMA and Material Flow Cost Accounting (MFCA) can also reveal environmental costs and resource inefficiencies that conventional financial accounting may overlook. For example, excessive water consumption during palm oil processing can increase wastewater generation and associated treatment requirements, while unrecovered methane represents both a greenhouse gas emission source and a lost renewable energy opportunity. Similarly, nutrient losses may reduce opportunities for fertilizer substitution, and unstable wastewater treatment operations can increase regulatory compliance risks and operational expenditures. MFCA is particularly relevant because it assigns monetary values to non-product outputs, including material, energy, system, and waste-management costs, thereby identifying inefficiencies throughout the production and treatment processes [13]. This approach shifts environmental accounting from recording downstream waste-management expenses toward identifying upstream resource losses and opportunities for operational improvement.

However, the effectiveness of EMA depends heavily on the availability, accuracy, and integration of operational and financial information. Palm oil mills may experience limitations associated with incomplete wastewater flow measurements, inconsistent environmental cost allocation, inadequate monitoring infrastructure, and fragmented data management across departments. These limitations can reduce the reliability of material balances and prevent the accurate valuation of recovered resources. Future research should therefore examine the organizational and technical requirements for implementing EMA in POME management, particularly data governance, measurement accuracy, cost allocation procedures, and coordination among engineering, finance, environmental management, and sustainability personnel. Strengthening these institutional capabilities is essential for transforming environmental accounting from a reporting function into a practical decision-support mechanism [9–15, 31].

4.3. ISO 14001 Alignment and Implementation Barriers.

ISO 14001 provides a structured mechanism for integrating POME treatment and resource recovery into routine environmental management practices rather than treating them as isolated technological initiatives. Through the Plan-Do-Check-Act (PDCA) cycle, palm oil mills can connect environmental risks and resource recovery opportunities with measurable organizational objectives. During the planning stage, significant environmental aspects can be assessed alongside resource efficiency opportunities, while implementation activities can establish operational controls, responsibilities, monitoring procedures, and emergency response measures. The performance evaluation stage can incorporate conventional environmental indicators together with EMA-based measurements, including wastewater treatment costs per cubic metre, recovered energy per unit of wastewater, material loss costs, avoided energy purchases, and net financial benefits from resource recovery. Management reviews and corrective actions can subsequently determine whether treatment and recovery initiatives achieve their intended environmental and economic objectives [16–19].

An important concern is that ISO 14001 certification may become primarily a documentation and compliance exercise rather than an effective mechanism for improving environmental performance. Although previous studies have associated environmental management systems with improved environmental outcomes, certification alone does not guarantee successful waste valorization, circular resource utilization, or economic optimization [17–19]. The effectiveness of ISO 14001 implementation therefore depends on the relevance

of environmental objectives, reliability of performance measurements, effectiveness of operational controls, and management commitment to continual improvement. Future investigations should distinguish between formal certification and substantive integration of environmental and economic performance indicators into organizational decision-making. This distinction is particularly important when evaluating whether ISO 14001 contributes directly to measurable improvements in POME treatment, resource recovery, and economic performance.

Implementation barriers may be particularly significant for small and medium-sized palm oil mills with limited financial, technical, and organizational resources. Establishing reliable environmental accounting and monitoring systems requires investment in flow meters, laboratory analyses, methane measurement equipment, data management systems, and personnel training. Incomplete operational records and inconsistent cost allocation can further complicate the integration of engineering and financial information, while fragmented responsibilities across environmental, maintenance, and finance departments may limit effective coordination. Smaller facilities may also face difficulties accessing reliable energy utilization infrastructure or markets for recovered products. A phased implementation strategy could begin with existing regulatory monitoring data, basic wastewater and energy records, and the establishment of a small cross-functional management team. Subsequent stages could involve instrument calibration, baseline environmental cost assessment, pilot resource recovery initiatives, and gradual integration of MFCA and investment evaluation. Such an approach may improve implementation feasibility while reducing the risk of establishing resource-intensive *reporting systems that provide limited managerial value.*

4.4. Priority Research Directions.

The critical synthesis identifies several research priorities for advancing POME management from fragmented technological, accounting, and governance approaches toward an integrated sustainability framework. As summarized in Table 5, future research should prioritize mill-level empirical investigations that combine mass balances, energy flows, environmental performance measurements, and financial information within longitudinal datasets. Such studies would enable researchers to examine whether integrating physical and monetary environmental accounting with ISO 14001-based management systems improves environmental outcomes and economic decision-making. Furthermore, standardized EMA and MFCA indicators should be developed and validated to support consistent measurement of wastewater treatment costs, recovered energy value, fertilizer substitution benefits, material loss costs, avoided emissions-related expenditures, and net economic performance. These indicators would provide a stronger foundation for comparing resource recovery strategies across mills with different operational characteristics. To translate these research priorities into practical applications, future investigations should adopt a multidisciplinary approach that integrates engineering measurements, environmental accounting, and organizational performance assessment. Particular emphasis should be placed on developing standardized measurement protocols, establishing reliable environmental and financial databases, and evaluating the feasibility of resource recovery technologies under different operational conditions. Longitudinal and comparative studies across palm oil mills of varying capacities would provide stronger evidence of implementation effectiveness and economic viability.

Furthermore, collaboration among researchers, industry practitioners, and policymakers could facilitate the development of practical guidelines and performance benchmarks.

Table 5. Priority Research Agenda Derived from the Critical Synthesis.

Research priority	Key question	Suggested evidence	Practical outcome / observable indicator
Mill-level integration	Can physical, monetary, and governance data be linked in one POME decision system?	Longitudinal case studies with mass, energy, cost, and performance data	Complete monthly POME balances; % costs traceable to recovery steps
Standardized valuation	Which indicators consistently capture environmental and economic value?	Validated EMA and MFCA indicator sets	Comparable cost/m³; value/kWh; non-product output cost
Technology comparison	Which recovery pathway performs best under comparable system boundaries?	Techno-economic and life-cycle comparison	Net present value; avoided emissions/t FFB; residual COD
ISO 14001 integration	Does embedding EMA metrics in PDCA improve performance?	Before-after or multi-site comparative studies	Audit closure; KPI performance change; recovery performance
Organizational capability	What prevents adoption of integrated POME management?	Interviews, surveys, and implementation studies	Meter coverage; staff competence; data completeness (%)

4.5. Reporting Limitations and Required Audit Trail.

The source manuscript reports a synthesis of 38 publications; however, its reference list contains 38 entries, several of which are standards, institutional reports, and methodological guidance rather than peer-reviewed studies. This discrepancy does not necessarily indicate an inconsistency, as some publications may have been included in the original bibliometric analysis without being cited directly in the manuscript. Nevertheless, the incomplete bibliographic information prevents independent reconstruction and verification of the literature screening process, study-level quality assessments, and thematic classifications. Providing the original search records, a complete list of included publications, database-specific search results, detailed inclusion and exclusion criteria, and the original VOSviewer datasets would improve methodological transparency, reproducibility, and reliability. Consequently, the thematic proportions presented in Figure 2 and the bibliometric interpretations illustrated in Figures 3–5 should be regarded as descriptive findings reproduced from the original manuscript rather than independently recalculated bibliometric results. Furthermore, the proposed methodological refinements described in Section 2 should be clearly distinguished from procedures actually implemented during the original review and verified against the available research documentation before publication.

5. Conclusion

Palm oil mill effluent (POME) management is evolving from conventional wastewater treatment and pollution control toward the recovery of methane, renewable energy, nutrients, and reusable water. However, the recovery of valuable resources does not necessarily guarantee environmental improvements or positive net economic returns. The reviewed literature identifies complementary technological, environmental accounting, and governance approaches, although empirical evidence of their coordinated implementation at the palm oil mill level remains limited. To address this gap, the proposed integrative framework establishes distinct but interconnected functions. Wastewater treatment and resource recovery systems quantify influent characteristics, pollutant loads, emissions, and recovered resources. Physical

Environmental Management Accounting (EMA) supports the reconciliation of material and energy flows, while Monetary EMA and Material Flow Cost Accounting (MFCA) quantify avoided expenditures, attributable environmental costs, and material losses. ISO 14001 subsequently integrates these indicators into environmental objectives, operational controls, internal audits, management reviews, and corrective actions to support systematic performance evaluation and continual improvement. From a practical perspective, palm oil mill operators should prioritize measurable indicators, including POME generation per tonne of fresh fruit bunches, effluent chemical oxygen demand (COD) and biochemical oxygen demand (BOD), actual methane capture, useful energy substitution, wastewater treatment and recovery costs per cubic metre, and non-product output costs. These indicators should be evaluated against documented operational baselines and consistent system boundaries to support reliable comparisons among treatment and resource recovery alternatives. Although the proposed framework offers a conceptual approach to improving environmental monitoring, cost transparency, resource efficiency, and sustainability governance, its effectiveness and economic feasibility require further validation through empirical mill-level investigations. Future research should therefore examine integrated technological, accounting, and management practices using longitudinal operational and financial data. Furthermore, the original literature search records, complete inventory of 38 included studies, study-level quality assessment documentation, and bibliometric datasets should be verified to strengthen the transparency, reproducibility, and methodological reliability of the systematic review.

Author Contribution

All authors contributed equally to the conceptualization, methodology, data analysis, interpretation of the results, manuscript preparation, review, and editing. All authors read and approved the final version of the manuscript.

Competing Interest

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this study.

References

[1] Ahmed, Y.; Yaakob, Z.; Akhtar, P.; Sopian, K. (2015). Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). *Renewable and Sustainable Energy Reviews*, *42*, 1260–1278. https://doi.org/10.1016/j.rser.2014.10.073.

[2] Kristanti, R.A.; Hadibarata, T. (2021). Palm oil industries in Malaysia and possible treatment technologies for palm oil mill effluent: A review. *Journal of Environmental Research, Engineering and Management*, *77*, 50–65. https://doi.org/10.5755/j01.erem.77.3.29522.

[3] Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

[4] Kirchherr, J.; Reike, D.; Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

[5] Kaniapan, S.; Hassan, S.; Ya, H.; Nesan, K.P. (2021). The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: A review. *Sustainability*.

[6] Suksaroj, C.; Jearat, K.; Cherypiew, N.; Rattanapan, C.; Suksaroj, T.T. (2023). Promoting circular economy in the palm oil industry through biogas codigestion of palm oil mill effluent and empty fruit bunch pressed wastewater. *Water*.
[7] Utami, N.U.; Said, M.; Faizal, M.; Komariah, L.N. (2019). Conversion of palm oil mill effluent on biogas production with consortium bacteria. *International Journal on Advanced Science, Engineering and Information Technology*, *9*, 2035–2041.
[8] Yunaningsih, A.; Satriadi, Y.; Mauluddin, A. (2024). Indikator sirkularitas di dalam tata kelola limbah pabrik kelapa sawit studi kasus: Limbah cair POME pabrik kelapa sawit. *JPPI*, *10*, 888–898.
[9] United Nations. (2001). Environmental Management Accounting Procedures and Principles; United Nations: New York, NY, USA.
[10] International Federation of Accountants. (2021). Putting the Focus on Environmental Management Accounting; IFAC: New York, NY, USA.
[11] Christ, K.L.; Burritt, R.L. (2013). Environmental management accounting: The significance of contingent variables for adoption. *Journal of Cleaner Production*, *41*, 163–173. https://doi.org/10.1016/j.jclepro.2012.10.007.
[12] Mokhtar, N.; Jusoh, R.; Zulkifli, N. (2016). Corporate characteristics and environmental management accounting implementation: Evidence from Malaysian public listed companies. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.01.085.
[13] Schaltegger, S.; Zvezdov, D. (2014). Expanding material flow cost accounting: Framework, review and potentials. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2014.08.040.
[14] Burritt, R.L.; Schaltegger, S. (2010). Sustainability accounting and reporting: Fad or trend? *Accounting, Auditing & Accountability Journal*. https://doi.org/10.1108/09513571011080144.
[15] Schaltegger, S. (2017). Linking environmental management accounting: A reflection on missing links to sustainability and planetary boundaries. *Social and Environmental Accountability Journal*, 1–11. https://doi.org/10.1080/0969160X.2017.1395351.
[16] International Organization for Standardization. (2015). ISO 14001: Environmental Management Systems – Requirements with Guidance for Use; ISO: Geneva, Switzerland.
[17] Muktiono, E.; Soediantono, D. (2022). Literature review of ISO 14001 environmental management system benefits and proposed applications in the defense industries. *Journal of Industrial Engineering & Management Research*, *3*, 1–12.
[18] Puglieri, F.N.; Ferreira, M.B.; Carlos, A.; Junior, F.; Piekarski, C.M.; et al. (2024). How to consider life cycle thinking into ISO 14001? A step-by-step method for small and medium-sized companies and a case study in waste management. *[Journal]*, 1–30.
[19] Sonder, J.; Sambung, R.; Kristinae, V.; Christa, U.R. (2025). Evaluating the impact of green SCOR and ISO 14001-based practices on sustainability in palm oil supply chains. *International Journal of Applied Finance and Business Studies*, *13*, 130–138.
[20] Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71.
[21] Ho, Q.N.; Lau, W.J.; Jaafar, J.; Othman, M.H.D.; Yoshida, N. (2025). Membrane technology for valuable resource recovery from palm oil mill effluent (POME): A review. *Membranes*, *15*, 138. https://doi.org/10.3390/membranes15050138.
[22] Ariadhy, S.Y.; Arkum, D. (2023). Sustainable palm oil governance: A case study of sustainable palm oil certification in Indonesia. *Proceedings of ICOSEAT 2022*; pp. 334–343.
[23] Sagala, D.; Frimawaty, E.; Sodri, A. (2025). Discovering the potential of renewable energy from palm oil mill effluent: Environmental impacts, opportunities, and challenges in the development of biogas and bio-CNG. *Bioculture Journal*, *2*, 106–122.

[24] Rendon-Camargo, D.; Boom-Carcamo, E.; Buelvas-Gutierrez, L. (2026). Utilization of oil palm residual biomass within the framework of industrial symbiosis: A systematic review of the economic sectors involved in its valorization. *Biomass*, 1–23. https://doi.org/10.3390/biomass6010010.

[25] Kacaribu, A.A.; Aisyah, Y.; Febriani, F.; Darwin. (2025). Development of wastewater treatment methods for palm oil mill effluent (POME): A comprehensive review. *Resources, Chemicals and Materials*, *4*, 100130. https://doi.org/10.1016/j.recm.2025.100130.

[26] Juan, V.; Molina, F.; Pe, M.; Ram, A.A. (2024). Evaluation of anaerobic digestion of palm oil mill effluent using different sludges as inoculum. *Water Resources and Industry*, *31*, 100247. https://doi.org/10.1016/j.wri.2024.100247.

[27] Akuma, S.O.; Yazdi, S.K.; Eze, U. (2026). A review of resource recovery from palm oil mill effluent (POME): Recent technological innovations and pathways to circular economy. *Next Sustainability*, *7*, 100261. https://doi.org/10.1016/j.nxsust.2026.100261.

[28] Ahmad, A.L.; Ismail, S.; Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination*, *157*, 87–95. https://doi.org/10.1016/S0011-9164(03)00387-4.

[29] Imam, S.S.; Sani, S.; Mujahid, M.; Adnan, R. (2025). Valuable resources recovery from palm oil mill effluent (POME): A short review on sustainable wealth reclamation. *Waste Management Bulletin*, *3*, 1–16. https://doi.org/10.1016/j.wmb.2024.12.002.

[30] Suhartono, M.J.; Theresia, M.; Budiastuti, S. (2025). Enhancing oil palm productivity and lowering emissions through the application of local organic waste. *Journal of Ecological Engineering*, *26*, 80–90.

[31] Swalih, M.M.; Ram, R.; Tew, E. (2024). Environmental management accounting for strategic decision-making: A systematic literature review. *Business Strategy and the Environment*, 6335–6367. https://doi.org/10.1002/bse.3828.

[32] Putra, B.A.; Aipassa, M.I.; Ruslim, Y.; Sihanjaya, M.E. (2025). Corporate environmental compliance and sustainability in palm oil plantation activities. *JBKL Jurnal Bisnis Kehutanan dan Lingkungan*, *3*, 1–17.

[33] OECD. (2023). Sustainability Policies and Practices for Corporate Governance in Asia; OECD Publishing: Paris, France.

[34] Hasan, F.; Ahmad, T.; Hidayat, A.N.; Fahmid, M.M. (2021). Driving sustainability in Indonesia's palm oil sector: The role of the Indonesian Government's certification system (ISPO). *INDEF Policy Brief*, *1*.

[35] Wicaksono, D.A.; Rifin, A.; Pahan, I. (2018). The sustainability of three Indonesian palm oil business entities. *Jurnal Manajemen & Agribisnis*, *15*, 249–257.

[36] Firdaus, T.; Lailatul, F.; Alifiyah, N. (2025). Circular economy in the palm oil industry: Global trends, potentials, and opportunities for green economy in Indonesia. *International Journal of Oil Palm*, *8*, 1–16. https://doi.org/10.35876/ijop.v8i2.125.

[37] Aliyu Yaro, N.S.; Adedeji, J.A.; Ngubane, Z.; Ikotun, J.O. (2026). Sustainability: A Comprehensive Overview of Palm Oil Waste Upcycling in Civil Engineering Applications. *Construction Materials*, *6*, 23. https://doi.org/10.3390/constrmater6020023.

[38] Zhang, X.; Zhang, M.; Zhang, H.; Jiang, Z.; Liu, C.; et al. (2020). A review on energy, environment and economic assessment in remanufacturing based on life cycle assessment method. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.120160.



© 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).