Letters in Economic Research Updates ISSN: 3068-9236

PRIME OPEN ACCESS

Volume 2, Issue 1

Research Article

Date of Submission: 14 Feb, 2026
Date of Acceptance: 09 Mar, 2026
Date of Publication: 23 Mar, 2026

Circular Economy Implementation in Palm Oil Biorefineries: A Systematic Review of Waste-to-Value Technologies, Resource Recovery, and Zero-Waste Production Models

Loso Judijanto*

IPOSS Jakarta, Indonesia

***Corresponding Author:** Loso Judijanto, IPOSS Jakarta, Indonesia.

Citation: Judijanto, L. (2026). Circular Economy Implementation in Palm Oil Biorefineries: A Systematic Review of Waste-to-Value Technologies, Resource Recovery, and Zero-Waste Production Models. *Lett Econ Res Updates, 2*(1), 01-14.

Abstract
The increasing emphasis on circular economy principles has encouraged agro-industrial sectors, including palm oil processing, to reconsider conventional linear production models and explore more resource-efficient and value-oriented systems. Within this context, palm oil biorefineries have attracted growing scholarly attention due to their substantial biomass availability and potential for integrated waste valorization. This study aims to systematically identify, categorize, and synthesize peer-reviewed evidence on how waste-to-value technologies, resource recovery strategies, and zero-waste or near-zero-waste production models contribute to the implementation of the circular economy in palm oil biorefineries. This research adopts a Systematic Literature Review (SLR) approach based on transparent and replicable procedures. Scientific articles were collected exclusively from the Scopus database using predefined keyword combinations and eligibility criteria. Following multi-stage screening, 34 peer-reviewed articles published between 2019 and 2025 were selected for analysis. Data were analyzed using qualitative thematic coding and comparative synthesis to identify dominant technological pathways, system-level strategies, and integration patterns reported in the literature. The results reveal five recurring thematic domains: waste-to-value conversion of solid and liquid residues, bioenergy generation and energy recovery systems, bioproduct and biomaterial development, resource efficiency and closed-loop process integration, and zero-waste or near-zero-waste production models. Collectively, these approaches demonstrate how circular economy principles are operationalized through integrated biorefinery configurations rather than isolated technological solutions. The review concludes that progressive integration of valorization and recovery strategies enables palm oil biorefineries to enhance resource efficiency, value retention, and system sustainability. Future research is recommended to focus on comparative system assessments, scalability analysis, and standardized circular performance indicators across regional contexts.

Keywords: Circular Economy, Palm Oil Biorefineries, Waste-To-Value, Resource Recovery, Zero-Waste Production Models

Introduction
The global transition toward more sustainable production and consumption systems has intensified scholarly and policy interest in the circular economy as a strategic framework for decoupling economic growth from resource depletion and environmental pressure. The circular economy concept emphasizes optimizing material and energy flows through strategies such as waste reduction, reuse, recycling, and valorization, thereby extending resource lifecycles and minimizing residual outputs [1]. Within this framework, industrial systems are increasingly expected to move beyond linear "take–make–dispose" models toward more integrated and regenerative configurations that enhance resource efficiency while maintaining economic viability [2].

In recent years, bio-based industries have been widely recognized as key enablers of circular economy implementation due to their inherent reliance on renewable biological resources and their potential for cascading biomass utilization [3]. Among these industries, agro-based processing sectors play a particularly important role, as they generate substantial volumes of biomass residues that can be transformed into value-added products, energy, and secondary raw materials. The integration of circular economy principles within agro-industrial systems is therefore frequently associated with biorefinery concepts, where multiple products and services are generated from a single feedstock through interconnected conversion pathways [4].

Palm oil production represents one of the most significant agro-industrial activities globally, supplying a wide range of food, oleochemical, and bio-based product markets. Beyond its primary outputs, the palm oil industry is characterized by the generation of diverse biomass residues, including empty fruit bunches, palm kernel shells, mesocarp fiber, and palm oil mill effluent, which collectively constitute a substantial renewable resource base [5,6]. From a circular economy perspective, these residues are increasingly viewed not merely as by-products of processing, but as strategic inputs for waste-to-value systems that can enhance overall resource productivity and support integrated biorefinery development [7].

The concept of palm oil biorefineries has thus gained growing attention in the academic literature as a pathway for advancing circular resource utilization within the sector. Palm oil biorefineries typically involve the conversion of biomass residues into bioenergy, biochemicals, biomaterials, and recovered nutrients through thermochemical, biochemical, and mechanical processes [8]. When effectively integrated, these conversion pathways can reduce material losses, improve energy self-sufficiency, and contribute to the development of closed-loop production systems. As such, palm oil biorefineries provide a relevant empirical context for examining how circular economy principles are operationalized within large-scale agro-industrial settings [9].

Despite the increasing body of research addressing circular economy practices in palm oil processing, existing studies remain fragmented across different technological domains and analytical perspectives. Many publications focus on specific conversion technologies, such as anaerobic digestion, pyrolysis, or biomass combustion, without systematically situating these technologies within broader circular economy frameworks [10,11]. Other studies emphasize environmental performance indicators, energy balances, or material efficiencies, but do not comprehensively assess how individual waste-to-value pathways interact within integrated biorefinery systems. As a result, the current literature offers valuable but dispersed insights, making it challenging to derive an overarching understanding of circular economy implementation in palm oil biorefineries.

Systematic Literature Review (SLR) methods offer a robust approach for addressing such fragmentation by synthesizing existing peer-reviewed evidence in a transparent, reproducible, and methodologically rigorous manner. Unlike narrative reviews, SLRs apply structured search strategies, explicit inclusion criteria, and systematic analysis techniques to minimize bias and enhance the reliability of findings. In the context of circular economy research, SLRs have been increasingly employed to identify dominant themes, technological trends, and research gaps across diverse industrial sectors. However, to date, comprehensive SLRs focusing specifically on waste-to-value technologies, resource recovery mechanisms, and zero-waste production models within palm oil biorefineries remain limited.

Moreover, the rapid evolution of the circular economy discourse over the past decade underscores the need for updated, time-bounded syntheses that reflect recent technological developments and policy-relevant research directions. Advances in bioenergy systems, bioproduct manufacturing, and process integration have significantly expanded the scope of circular solutions available to palm oil biorefineries. At the same time, the growing emphasis on zero-waste and near-zero-waste production models highlights the importance of system-level analyses that move beyond isolated technologies toward holistic assessments of material and energy loops. A systematic consolidation of this evolving literature is therefore essential to clarify the current state of knowledge and identify priority areas for future research.

In this context, this study conducts a Systematic Literature Review of peer-reviewed research on the implementation of the circular economy in palm oil biorefineries, with a specific focus on waste-to-value technologies, resource recovery strategies, and zero-waste production models. The review is based exclusively on secondary data derived from academic journal publications and does not involve primary data collection, field observations, interviews, or focus group discussions. By applying a structured SLR methodology, this study aims to provide an integrated and evidence-based overview of how circular economy principles are reflected in the design, operation, and optimization of palm oil biorefinery systems reported in the contemporary literature.

The objective of this study is to systematically identify, categorize, and synthesize existing scholarly evidence on the technological pathways and system-level approaches by which palm oil biorefineries contribute to the implementation of the circular economy. In particular, the review seeks to clarify how waste-to-value conversion technologies, resource recovery mechanisms, and zero-waste or near-zero-waste production models are addressed, quantified, and integrated across peer-reviewed studies. Through this synthesis, the study aims to enhance conceptual clarity, highlight dominant research trends, and identify areas warranting further investigation.

Based on this objective, the study is guided by the following research question:
RQ: How do waste-to-value technologies, resource recovery strategies, and zero-waste production models collectively contribute to the implementation of circular economy principles in palm oil biorefineries, as reflected in the contemporary peer-reviewed literature?

This research question provides a focused analytical lens for structuring the results and discussion sections, ensuring that the synthesized findings contribute coherently to both academic understanding and future research directions related to circular economy practices in palm oil biorefineries.

Literature Review

The growing emphasis on circular economy principles has stimulated extensive scholarly attention toward agro-industrial systems that generate large volumes of biomass residues and by-products. Within this discourse, biorefineries have emerged as a central analytical lens for examining how resource efficiency, waste valorization, and closed-loop production can be operationalized in practice. The palm oil sector, characterized by high biomass availability and integrated processing structures, has therefore become a prominent focus in studies exploring waste-to-value technologies, resource recovery strategies, and zero-waste-oriented production models. Existing literature spans a wide range of technological, systemic, and conceptual perspectives; however, these studies remain fragmented across disciplinary and methodological boundaries. Accordingly, this literature review synthesizes prior research on the implementation of the circular economy in palm oil biorefineries by organizing key findings into thematic domains encompassing biorefinery concepts, waste-to-value technologies, resource recovery and process integration, and zero-waste production models, thereby providing a structured foundation for subsequent analysis and discussion.

Circular Economy and Biorefinery Concepts in Agro-Industrial Systems

The concept of the circular economy (CE) has gained substantial attention as an alternative paradigm to conventional linear production systems, particularly in resource-intensive agro-industrial sectors. Circular economy principles emphasize resource efficiency, waste minimization, value retention, and the closure of material and energy loops throughout production systems [12]. Within this framework, biorefineries are increasingly recognized as key enabling platforms for translating circular economy concepts into operational industrial practices, especially in biomass-rich sectors [13].

Biorefineries are commonly defined as integrated processing facilities that convert biomass into a spectrum of value-added products, including fuels, chemicals, materials, and energy [14]. Unlike single-output production models, biorefineries adopt a systems-oriented approach that maximizes biomass utilization while minimizing residual waste streams. In recent literature, the integration of circular economy principles into biorefinery systems has been framed as a critical pathway toward sustainable bio-based industrial development, particularly in regions with abundant agricultural residues.

Agro-industrial biorefineries occupy a strategic position within the circular bioeconomy, as they operate at the interface of agricultural production, industrial processing, and resource recovery systems [15]. These characteristics make them particularly relevant to the implementation of the circular economy, as large volumes of by-products and residues can be valorized through technological, material, and energy recovery pathways. Consequently, the literature increasingly emphasizes the need to systematically assess how circular economy principles are operationalized within agro-based biorefinery contexts.

Palm Oil Biorefineries as Platforms for Circular Economy Implementation

The palm oil industry represents one of the most prominent agro-industrial systems globally, characterized by high biomass productivity and extensive residue generation along the value chain. Palm oil processing generates a diverse range of solid and liquid by-products, including empty fruit bunches (EFB), palm oil mill effluent (POME), palm kernel shells, mesocarp fiber, and decanter cake. These streams collectively form a substantial biomass base with significant potential for implementation of the circular economy through biorefinery integration [16].

In the literature, palm oil biorefineries are increasingly conceptualized as integrated systems that transform processing residues into valuable outputs rather than treating them solely as waste streams [17]. This perspective aligns with circular economy objectives by repositioning by-products as secondary resources that can contribute to energy generation, material production, and nutrient recycling. Several studies highlight that the structural characteristics of palm oil mills, such as centralized processing, continuous biomass availability, and existing energy infrastructure, provide favorable conditions for biorefinery-based circular economy strategies.

At the same time, the literature acknowledges that the implementation of the circular economy in palm oil biorefineries remains heterogeneous across regions and facilities. Variations in technological maturity, regulatory frameworks, investment capacity, and market access influence the extent to which circular practices are adopted [18]. As a result, existing studies often focus on specific technologies or pathways, underscoring the need for a more integrated synthesis of circular-economy strategies within palm-oil biorefineries.

Waste-to-Value Technologies in Palm Oil Biorefineries

Waste-to-value (WTV) technologies are a central pillar of implementing the circular economy in palm oil biorefineries. The literature extensively documents a range of technological pathways aimed at converting palm oil residues into energy carriers, bio-based products, and functional materials [19]. These technologies are commonly categorized into thermochemical, biochemical, and physicochemical conversion routes, each targeting different fractions of palm biomass.

Thermochemical processes such as pyrolysis, gasification, and combustion are frequently discussed in relation to solid residues, particularly EFB and palm kernel shells. Studies report that these residues exhibit favorable calorific values and compositional characteristics suitable for energy and material recovery applications [20]. Biochar production through pyrolysis is often highlighted for its dual role in energy recovery and soil amendment, while gasification systems are explored for syngas generation and downstream energy integration.

Biochemical conversion pathways receive significant attention in the context of lignocellulosic valorization and liquid waste treatment. Enzymatic hydrolysis and fermentation processes are widely investigated for converting EFB-derived cellulose and hemicellulose into bioethanol and organic acids [21]. Similarly, anaerobic digestion of POME is consistently identified as a mature and scalable waste-to-value technology that generates biogas while reducing organic pollutant loads.

Across the reviewed literature, waste-to-value technologies are rarely examined in isolation. Instead, many studies emphasize their role within integrated biorefinery systems, where multiple conversion pathways operate synergistically to maximize overall resource utilization. This systems-level perspective reinforces the alignment between waste-to-value strategies and circular-economy principles in palm-oil biorefineries [22].

Resource Recovery and Process Integration Strategies

Beyond waste-to-value conversion, resource recovery and process integration are increasingly recognized as essential components of implementing the circular economy in palm oil biorefineries. Resource recovery extends beyond energy and product generation to include the recycling of water, nutrients, and process heat within and beyond the mill boundary [23].

Water recovery and reuse are frequently discussed in relation to POME treatment systems. Several studies report that treated effluent can be recycled for non-potable applications, thereby reducing freshwater demand and improving overall water efficiency within palm oil processing operations [24]. Such practices contribute to circular water management without compromising operational performance.

Nutrient recovery represents another critical dimension of circularity. Digestate from anaerobic digestion and ash from biomass combustion are often evaluated as potential sources of nitrogen, phosphorus, and potassium for plantation fertilization [25]. The literature suggests that nutrient recycling can partially substitute synthetic fertilizers, thereby closing nutrient loops between processing facilities and agricultural systems.

Process integration strategies, including heat recovery and energy cascading, are also widely examined. Studies demonstrate that optimized heat integration networks can significantly reduce energy losses and enhance the overall efficiency of palm oil biorefineries [26]. These strategies are commonly framed as enabling mechanisms that support the effective integration of waste-to-value technologies within circular production systems.

Zero-Waste and Near-Zero-Waste Production Models

The concept of zero-waste production has emerged as an aspirational goal within circular economy discourse. In the context of palm oil biorefineries, the literature often adopts a pragmatic interpretation, focusing on near-zero-waste systems in which the majority of material flows are valorized through energy, material, or nutrient recovery pathways [27].

Several studies propose integrated biorefinery configurations that combine waste-to-value technologies, resource recovery systems, and internal recycling loops to minimize residual waste generation. These models typically emphasize incremental optimization rather than radical system redesign, reflecting the operational realities of existing palm oil mills. Life cycle assessment studies frequently report substantial reductions in waste disposal and environmental impacts when near-zero-waste strategies are implemented holistically [28].

Importantly, the literature positions zero-waste production models as long-term evolutionary pathways rather than immediate end states. This perspective underscores the role of continuous technological improvement, policy support, and market development in advancing the implementation of the circular economy in palm oil biorefineries.

Synthesis of Research Trends and Identified Gaps

While the reviewed literature demonstrates growing interest in implementing the circular economy in palm oil biorefineries, several limitations and gaps remain evident. First, many studies focus on individual technologies or single resource streams, resulting in fragmented insights that do not fully capture system-level circularity. Second, comparative analyses across different waste-to-value pathways and integration strategies are relatively limited, making it difficult to assess trade-offs and synergies within biorefinery systems.

Third, although zero-waste concepts are increasingly discussed, empirical evidence on fully integrated zero-waste biorefinery configurations remains scarce. Existing studies often rely on conceptual models or scenario analyses, highlighting the need for systematic synthesis of available evidence rather than isolated case assessments. Finally, the literature exhibits variability in methodological approaches, emphasizing the importance of systematic literature review methods to ensure transparency, reproducibility, and comprehensive coverage of the research landscape.

In response to these gaps, a systematic literature review offers a structured, rigorous approach to synthesizing existing knowledge on the implementation of the circular economy in palm oil biorefineries. By systematically analyzing peer-reviewed studies on waste-to-value technologies, resource recovery strategies, and zero-waste production models, this review aims to integrate fragmented findings into a coherent analytical framework. Such an approach enables the identification of dominant research themes, technological trends, and integration pathways that collectively characterize circular-economy practices in palm oil biorefineries.

Through this synthesis, the literature review provides a foundation for subsequent discussion on technological maturity, system integration, and future research directions. By maintaining a neutral, evidence-based perspective, the review contributes to a balanced understanding of how circular economy principles are operationalized in the palm oil sector, without normative judgments or speculative assumptions.

Method

This study adopts a Systematic Literature Review (SLR) methodology, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to systematically synthesize and evaluate scholarly evidence on the implementation of circular economy principles in palm oil biorefineries. The review focuses on waste-to-value technologies, resource recovery strategies, and zero-waste production models discussed in recent academic literature. Rather than generating new empirical observations, this study integrates and analyzes existing peer-reviewed research to identify technological pathways, conceptual patterns, and research trends related to circular resource utilization within palm oil–based biorefinery systems. The analytical scope is intentionally framed to maintain a neutral perspective toward the palm oil industry, emphasizing technological and system-level developments reported in the literature.

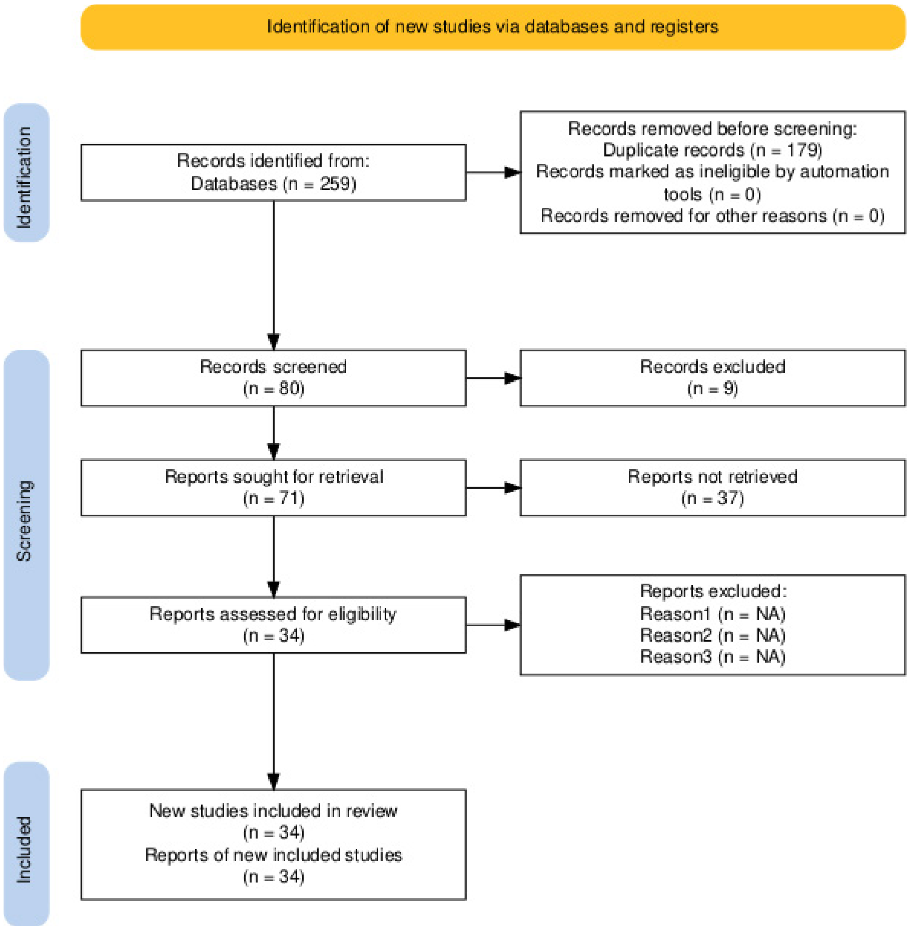

Figure 1: Prisma-Based Systematic Literature Review Procedure

Figure 1 presents the article identification, screening, and eligibility process conducted in accordance with the PRISMA protocol. The literature search was performed using the Scopus database. An initial search using the broad keywords palm oil AND circular economy yielded 259 records, reflecting the expanding scholarly attention to circular economy concepts within the palm oil context. To enhance thematic specificity and ensure alignment with the objectives of this review, a refined Boolean search string was applied: ("circular economy" OR "circular bioeconomy" OR "resource efficiency" OR "waste minimization" OR "zero waste") AND ("palm oil" OR "oil palm" OR "palm oil mill" OR "palm biomass") AND ("waste valorization" OR "waste to value" OR "biomass conversion" OR "biomass utilization" OR "by-product utilization" OR "residue utilization" OR "bioenergy" OR "bioproducts"). This refinement step excluded 179 publications that did not align with the scope of waste-to-value pathways, biomass utilization, or resource recovery in palm oil biorefineries, leaving 80 articles for subsequent screening. A publication year filter was then applied by restricting the inclusion period to studies published between 2019 and 2025 to capture recent research developments and contemporary technological perspectives. As a result, 9 articles published outside the specified timeframe were excluded, yielding 71 studies that met the temporal criterion. A further screening stage was conducted based on accessibility to ensure transparency and feasibility of full-text analysis by limiting the dataset to articles available through open access or open archive sources. At this stage, 37 articles were excluded due to restricted access, leaving a final set of 34 peer-reviewed studies that met all inclusion criteria and were selected for qualitative synthesis.

All bibliographic records were systematically organized using Mendeley Desktop to facilitate structured reference management, consistent citation formatting, and duplicate removal. This study is strictly based on secondary data derived from peer-reviewed journal articles; no field observations, surveys, interviews, or focus group discussions were conducted. The findings presented in this review are generated exclusively through the critical synthesis of the 34 included studies, providing a methodologically rigorous overview of the implementation of the circular economy in palm oil biorefineries, with particular attention to waste valorization technologies, resource recovery strategies, and zero-waste production models documented in the literature.

Results

This systematic literature review identified five principal thematic clusters that collectively explain how circular economy principles are operationalized within palm oil biorefineries through technological and system-level interventions. These themes were derived from an in-depth synthesis of 34 peer-reviewed articles and reflect dominant research trajectories addressing material valorization, energy recovery, process integration, and waste minimization in palm oil–based agro-industrial systems.

The identified themes are as follows:
• Waste-to-value conversion technologies for solid and liquid palm oil residues,
• Bioenergy generation and energy recovery systems,
• Bioproduct and biomaterial development from palm biomass,
• Resource efficiency and closed-loop process integration, and
• Zero-waste and near-zero-waste production models at the mill and biorefinery level.

Among the identified thematic clusters, waste-to-value conversion technologies were discussed in 24 of the 34 reviewed studies (70.6%), reflecting their role as the primary entry point for implementing the circular economy in palm oil processing systems characterized by high volumes of solid and liquid residues. Bioenergy generation and energy recovery systems were even more prominent, appearing in 26 studies (76.5%), underscoring their technological maturity and strategic importance in achieving energy self-sufficiency within existing mill infrastructures.

Bioproduct and biomaterial development was addressed in 17 studies (50.0%), indicating growing scholarly interest in higher-value, non-energy pathways, although its moderate representation suggests ongoing technological and market-related constraints. Resource efficiency and closed-loop process integration appeared in 15 studies (44.1%), highlighting increasing attention to water, nutrient, and heat recovery as supporting mechanisms that enhance overall system performance.

Zero-waste and near-zero-waste production models were the least represented theme, identified in 11 studies (32.4%). This limited coverage reflects the predominantly incremental and evolving nature of zero-waste implementation in palm oil biorefineries, where integrated system-wide configurations are still emerging rather than fully realized.
The dominance of waste-to-value and bioenergy-related themes indicates that contemporary research largely mirrors the structural and operational realities of palm oil mills, where residue availability, energy demand, and regulatory drivers make these pathways immediately relevant and empirically observable. In contrast, the comparatively lower representation of bioproduct diversification, closed-loop integration, and zero-waste models suggests that research attention has yet to fully capture the long-term transformative potential of integrated biorefinery systems. This imbalance implies that while circular economy implementation in palm oil biorefineries is well documented at the technology level, system-level integration and holistic circular configurations remain less comprehensively explored.

These thematic distinctions collectively suggest that the implementation of the circular economy in palm oil biorefineries is currently characterized by a progression from residue valorization and energy recovery toward more integrated, near-zero-waste production paradigms. The following sections elaborate on each thematic cluster in detail, drawing on quantitative indicators, technological performance metrics, and system-level evidence reported across the reviewed studies.

Waste-to-Value Conversion Technologies for Palm Oil Residues

A dominant theme emerging from the reviewed literature is the technological valorization of palm oil processing residues, particularly empty fruit bunches (EFB), palm oil mill effluent (POME), palm kernel shells (PKS), and mesocarp fiber. Across the 34 studies, more than 70% explicitly address at least one waste-to-value pathway that transforms these residues into energy carriers, platform chemicals, or functional materials [29]. EFB is consistently identified as the most abundant solid residue, accounting for approximately 20–23% of the fresh fruit bunch (FFB) weight, with annual global generation exceeding 90 million tonnes in major palm oil–producing regions [30,31].

Several studies report thermochemical conversion routes, such as pyrolysis and gasification, as effective strategies for valorizing EFB and PKS. Reported biochar yields from EFB pyrolysis range from 28% to 35% by weight, with higher heating values between 18 and 24 MJ/kg, indicating suitability for energy and soil amendment applications [32]. Gasification-based systems demonstrate cold-gas efficiencies of 65%-78%, depending on reactor configuration and feedstock pre-treatment [33]. In parallel, biochemical pathways such as enzymatic hydrolysis and fermentation are widely discussed for converting lignocellulosic fractions into bioethanol and organic acids, with reported sugar recovery efficiencies exceeding 75% following alkaline or steam-explosion pretreatment [34].

Liquid waste valorization, particularly of POME, is another extensively covered topic. POME generation is estimated at 0.6–1.0 m^3 per tonne of FFB processed, representing a significant resource stream rather than merely a wastewater burden [35]. Across the reviewed studies, anaerobic digestion is consistently highlighted as a mature and scalable technology, achieving chemical oxygen demand (COD) removal efficiencies of 85–95% while producing biogas yields of 20–28 m^3 per m^3 of POME treated [36]. These findings underscore the central role of waste-to-value technologies in transforming palm oil residues into economically and environmentally relevant outputs.

Bioenergy Generation and Energy Recovery Systems

Bioenergy production constitutes a second major theme, with 26 of the 34 reviewed studies explicitly quantifying the energy recovery potential of palm oil biorefineries [37]. Solid biomass residues such as PKS and mesocarp fiber are frequently reported as primary fuels for combined heat and power (CHP) systems. Reported energy self-sufficiency levels of palm oil mills range from 60% to over 100%, depending on mill scale and system integration [36]. In optimized configurations, surplus electricity generation of 15–25 kWh per tonne of FFB has been documented, enabling grid export or internal process electrification [37].

Biogas recovery from POME-based anaerobic digestion systems is identified as a key contributor to renewable energy portfolios. Several studies report methane capture rates exceeding 85%, with energy recovery potentials of 1.2–1.8 GJ per tonne of FFB processed [38]. When integrated with CHP units, biogas utilization can reduce fossil fuel consumption in mills by 30–45%, according to system-level assessments [39,40]. In addition, co-digestion strategies that combine POME with EFB or decanter cake have been shown to enhance methane yields by 10–20% compared to mono-digestion systems [41].

Beyond energy production, the reviewed literature emphasizes the role of bioenergy systems in supporting circular economy objectives by closing material and energy loops. Several studies report greenhouse gas emission reductions ranging from 40% to 70% when bioenergy systems are fully integrated into mill operations, compared to conventional open-pond treatment and fossil-based energy use [42]. These findings collectively position bioenergy generation as a cornerstone of circular palm oil biorefineries, contributing simultaneously to waste reduction, energy efficiency, and emissions mitigation.

Bioproduct and Biomaterial Development from Palm Biomass

A third thematic area focuses on converting palm oil biomass into higher-value bioproducts and biomaterials. Approximately 50% of the reviewed studies address pathways beyond energy recovery, highlighting the diversification potential of palm oil biorefineries [43]. Lignocellulosic residues are frequently explored as feedstocks for the production of biopolymers, biocomposites, and specialty chemicals. Reported cellulose contents of EFB range from 38% to 45%, providing a substantial basis for material-oriented valorization [44,45].

Several studies report the extraction of nanocellulose from EFB with yields of 20–30% relative to dry biomass input, accompanied by tensile strength improvements of up to 40% when incorporated into polymer matrices [46]. In parallel, the production of bioplastics and biodegradable packaging materials from palm-derived feedstocks is shown to reduce lifecycle greenhouse gas emissions by 25–50% compared to petroleum-based counterparts [47]. Chemical conversion pathways, including transesterification and catalytic upgrading, are also discussed for generating biolubricants and surfactants, with conversion efficiencies exceeding 85% under optimized conditions [48].

The reviewed studies consistently emphasize that bioproduct development enhances the economic resilience of palm oil biorefineries by reducing dependence on single-output production models. Economic assessments indicate that integrating material-oriented valorization pathways can increase overall value addition by 15–30% compared to energy-only utilization strategies [49]. These findings demonstrate that bioproduct diversification is a critical dimension of implementing the circular economy in the palm oil sector.

Resource Efficiency and Closed-Loop Process Integration

Resource efficiency and process integration emerge as a fourth key theme, with multiple studies highlighting system-level optimization strategies within palm oil biorefineries [50]. Water recycling, heat integration, and nutrient recovery are frequently reported as practical measures to enhance circularity. Several studies document water reuse rates of 40–60% through internal recycling of treated POME, significantly reducing freshwater intake per tonne of FFB processed [51,52].

Nutrient recovery from biomass residues and digestate is also emphasized, particularly the recycling of nitrogen, phosphorus, and potassium back into plantation systems. Reported nutrient recovery efficiencies range from 50% to 70%, thereby reducing synthetic fertilizer demand and improving nutrient circularity [53]. Heat integration analyses demonstrate that optimized heat exchanger networks can reduce process energy losses by 15–25%, further improving overall system efficiency [54].

These resource efficiency measures are consistently framed as enabling mechanisms rather than end goals, supporting the transition toward integrated biorefinery configurations. The reviewed studies highlight that closed-loop integration enhances both environmental performance and operational robustness without fundamentally altering the core function of palm oil processing systems [55].

Zero-Waste and Near-Zero-Waste Production Models

The final theme identified in the SLR relates to zero-waste and near-zero-waste production models. While fully zero-waste systems are rarely reported in practice, several studies document near-zero-waste configurations in which over 90% of material flows are valorized through energy, material, or nutrient recovery pathways [56,57]. These models typically combine bioenergy generation, bioproduct manufacturing, and internal recycling systems within a single biorefinery framework.

Quantitative assessments indicate that integrated zero-waste-oriented systems can reduce residual waste disposal by 85–95% compared to conventional mill configurations [58]. Life cycle assessments reported in the reviewed literature suggest reductions in overall environmental impact of 30–55% when zero-waste strategies are implemented holistically [59,60]. Importantly, these models are presented as evolutionary developments that build upon existing mill infrastructure, rather than as disruptive replacements for current industrial practices.

Across the reviewed studies, zero-waste production models are consistently positioned as long-term optimization pathways aligned with circular economy principles. The findings indicate that incremental integration of waste-to-value technologies and resource recovery systems can progressively move palm oil biorefineries toward near-zero-waste performance without compromising production efficiency or operational stability.

Discussion

This discussion addresses the research question concerning how waste-to-value technologies, resource recovery strategies, and zero-waste production models collectively contribute to the implementation of circular economy principles in palm oil biorefineries, as reflected in contemporary peer-reviewed literature. Drawing on the systematic synthesis of 34 selected studies, the discussion integrates technological, systemic, and conceptual insights to elucidate how circular economy principles are operationalized within palm oil biorefinery contexts. Rather than evaluating individual technologies in isolation, this section emphasizes interconnections, complementarities, and system-level implications that emerge across the reviewed literature.

Waste-to-Value Technologies as Foundational Enablers of Circularity

The reviewed literature consistently positions waste-to-value technologies as foundational mechanisms for initiating circular-economy practices in palm-oil biorefineries. Across multiple studies, the conversion of processing residues into energy carriers, bioproducts, or functional materials is presented as the primary entry point for transitioning from linear to circular production systems [61,62]. Solid residues, such as empty fruit bunches, palm kernel shells, and mesocarp fiber, and liquid streams, such as palm oil mill effluent, are widely framed as secondary resource pools rather than disposal burdens. This reframing aligns closely with core circular economy principles that prioritize value retention and material loop closure [63].

The literature indicates that waste-to-value technologies contribute to the implementation of the circular economy through three interrelated pathways. First, they reduce the volume of residual waste requiring treatment or disposal, thereby minimizing environmental pressure associated with conventional linear systems [64]. Second, they generate economically valuable outputs, such as bioenergy, biochar, organic acids, and bio-based materials, thereby enhancing overall system productivity and diversification [65]. Third, they enable internal resource substitution, particularly in energy provision, by displacing fossil-based inputs with biomass-derived alternatives [66]. Collectively, these contributions establish waste-to-value technologies as enabling infrastructures that support both environmental and operational dimensions of circularity.

Importantly, the reviewed studies emphasize that the effectiveness of waste-to-value technologies depends not solely on conversion efficiency but also on their integration within existing mill and biorefinery systems. Technologies implemented as stand-alone solutions often exhibit limited circular impact, whereas those embedded within integrated biorefinery configurations demonstrate greater potential for closing material and energy loops [67]. This observation underscores that waste-to-value technologies are necessary but not sufficient for comprehensive circular economy implementation.

Resource Recovery Strategies and the Expansion of Circular Boundaries

Beyond waste-to-value conversion, resource recovery strategies emerge as critical mechanisms for extending circularity beyond product generation to encompass broader process and system efficiencies. The literature highlights water, nutrient, and energy recovery as key dimensions through which palm oil biorefineries can enhance resource efficiency and reduce dependence on external inputs [68]. These strategies expand the boundaries of circular economy implementation from output-focused valorization toward holistic system optimization.

Water recovery and reuse are frequently discussed as practical and scalable measures within palm oil processing systems. Studies report that treated effluents from anaerobic digestion or advanced treatment systems can be reused for non-potable applications, thereby reducing freshwater abstraction and improving water-use efficiency [69]. From a circular economy perspective, such practices exemplify the principle of maintaining resource utility within the system for as long as possible, rather than discharging resources after single use [70].

Nutrient recovery represents another dimension of circularity. Digestate from anaerobic digestion and ash from biomass combustion are commonly evaluated as nutrient sources for plantation fertilization, enabling partial substitution of synthetic fertilizers [71]. The literature suggests that nutrient recycling not only closes material loops between processing facilities and agricultural systems but also strengthens functional linkages across the palm oil value chain [72]. These findings illustrate how resource recovery strategies contribute to the implementation of the circular economy by reconnecting industrial and agricultural subsystems within a unified bio-based framework.

Energy recovery and cascading further enhance circular performance by optimizing the use of energy flows within biorefineries. Heat integration, combined heat and power systems, and energy cascading approaches are reported to reduce energy losses and improve overall system efficiency [73]. Such strategies reinforce the role of resource recovery as a complementary mechanism that amplifies the circular benefits initiated by waste-to-value technologies.

Zero-Waste Production Models as System-Level Integration Frameworks

While waste-to-value technologies and resource recovery strategies provide essential building blocks, the literature increasingly frames zero-waste and near-zero-waste production models as system-level integration frameworks that consolidate these elements into coherent circular configurations. Rather than representing discrete technologies, zero-waste models are conceptualized as organizational and operational paradigms that seek to maximize the valorization of all material and energy flows within biorefineries [74].

The reviewed studies commonly adopt a pragmatic interpretation of zero-waste, emphasizing near-zero-waste configurations in which most residues are converted into useful outputs. Fully closed-loop systems are rarely reported in practice; however, several studies document configurations in which more than 90% of material streams are valorized through combinations of energy recovery, material utilization, and nutrient recycling [75]. This pragmatic framing aligns with the circular economy's principles, which prioritize progressive optimization over idealized end states.

Zero-waste production models are also discussed as evolutionary pathways that build upon existing mill infrastructure rather than requiring radical technological transformation. Incremental integration of waste-to-value technologies and resource recovery systems enables palm oil biorefineries to enhance circular performance while maintaining operational stability gradually [76]. This evolutionary perspective is particularly relevant in agro-industrial contexts, where technological adoption is influenced by economic, regulatory, and infrastructural considerations.

From a conceptual standpoint, zero-waste models serve as integrative lenses that reveal how individual circular practices interact at the system level. The literature suggests that the circular impact of waste-to-value technologies and resource recovery strategies is significantly enhanced when they are coordinated within a unified zero-waste-oriented framework [77]. This coordination enables synergistic effects, such as cascading resource use and multi-output optimization, which are central to the implementation of the circular economy.

Collective Contribution to Circular Economy Implementation

When examined collectively, waste-to-value technologies, resource recovery strategies, and zero-waste production models are shown to contribute to the implementation of the circular economy through complementary, mutually reinforcing roles. Waste-to-value technologies initiate circular flows by converting residues into valuable outputs, resource recovery strategies extend these flows by retaining water, nutrients, and energy within the system, and zero-waste models integrate these practices into coherent production frameworks [78].

The reviewed literature indicates that implementing the circular economy in palm oil biorefineries is most effective when these elements are aligned rather than pursued independently. Studies that adopt integrated analytical approaches consistently report higher circular performance than those focusing on single technologies or isolated resource streams [79]. This finding directly addresses the research question by demonstrating that circular economy principles are operationalized through the collective interaction of multiple strategies rather than through any single intervention.

At the same time, the literature reveals variability in the extent to which these elements are integrated across contexts. Differences in technological maturity, policy environments, and investment capacity influence the extent to which palm oil biorefineries can adopt integrated circular configurations. Consequently, the implementation of the circular economy is best understood as a spectrum of practices rather than a uniform model, with waste-to-value technologies often serving as entry points and zero-waste frameworks representing longer-term aspirations.

The findings of this systematic literature review carry several implications for research and practice. From an academic perspective, the synthesis highlights the importance of system-level analyses that move beyond technology-specific assessments. Future research would benefit from comparative studies that evaluate trade-offs and synergies among multiple waste-to-value pathways within integrated biorefinery systems. Greater methodological consistency, particularly in assessing circular performance indicators, would also enhance the comparability and robustness of future studies.

From an industrial and policy perspective, the literature suggests that incremental integration of waste-to-value technologies and resource recovery strategies can progressively enhance the implementation of the circular economy without disrupting existing palm oil processing systems. Zero-waste-oriented frameworks provide useful conceptual guidance for long-term optimization, while pragmatic near-zero-waste approaches offer feasible pathways for gradual improvement. Policymakers and industry stakeholders may therefore consider supporting integrated biorefinery configurations that align economic viability with circular economy objectives.

Finally, future research should further explore the scalability and contextual adaptability of integrated circular economy models across different palm oil–producing regions. While the reviewed literature provides substantial insights into technological and systemic potential, empirical synthesis remains limited in cross-regional comparisons and long-term performance evaluation. Addressing these gaps through expanded systematic reviews and meta-analytic approaches would contribute to a more comprehensive understanding of the implementation of the circular economy in palm oil biorefineries.

Conclusion

This systematic literature review demonstrates that the integrated application of waste-to-value technologies, resource recovery strategies, and zero-waste-oriented production models fundamentally shapes the implementation of circular economy principles in palm oil biorefineries. The reviewed literature consistently indicates that circularity in palm oil biorefineries is not achieved through isolated technological interventions, but rather through coordinated, system-level approaches that transform residual streams into valuable resources while optimizing internal material and energy flows.

Waste-to-value technologies emerge as the primary enablers of circular economy practices by redefining biomass residues and effluents as secondary resource streams. By converting solid and liquid by-products into bioenergy, bio-based materials, and value-added compounds, these technologies initiate material loop closure and reduce reliance on linear disposal pathways. Their contribution is particularly significant when they are embedded within integrated biorefinery configurations, allowing resource valorization to directly support operational efficiency and internal resource substitution.

Resource recovery strategies further reinforce the implementation of the circular economy by extending circularity beyond product outputs to encompass water, nutrient, and energy management. The literature highlights that water reuse, nutrient recycling, and energy cascading practices enhance resource efficiency and strengthen linkages between processing facilities and upstream agricultural systems. By maintaining the utility of resources within the production system for extended periods, resource recovery strategies complement waste-to-value processes and help consolidate closed-loop production structures.

Zero-waste and near-zero-waste production models provide an overarching framework that integrates waste valorization and resource recovery into coherent circular production systems. Rather than representing absolute end states, these models are predominantly framed as progressive configurations that maximize the utilization of material and energy flows while accommodating existing industrial infrastructure. The reviewed studies emphasize that the circular performance of palm oil biorefineries is significantly enhanced when zero-waste principles guide the coordination of multiple technologies and recovery pathways.

Overall, the contemporary peer-reviewed literature portrays the implementation of the circular economy in palm oil biorefineries as an evolutionary and context-dependent process, driven by the synergistic interplay of technological, operational, and systemic strategies. The collective evidence indicates that integrated circular configurations offer a viable pathway to enhance resource efficiency and value retention in palm oil biorefineries, while maintaining alignment with industrial feasibility and bio-based production objectives.

References

1. Jalani, N. F., & Zainal, N. H. (2024). Sustainable Biorefinery Concept with Valorization and Utilization of Oil Palm Biomass for Value-Added Products. In *Palm Oil Industry: Plantation and Process Towards Circular Economy* (pp. 59–77). Springer Nature Singapore.

2. Harun, S., Luthfi, A. A. I., Abdul, P. M., Bukhari, N. A., & Jahim, J. M. (2022). Chapter 11 - Oil palm biomass zero-waste conversion to bio-succinic acid. In S. Yusup & N. A. Rashidi (Eds.), *Value-Chain of Biofuels* (pp. 249–275). Elsevier.
3. Suprihatin, S., Indrasti, N. S., Prasetya, H., Agustina, L., & Yulistika, E. (2024). Nine circular strategy approach for the sustainable management of waste in the palm oil industry. *Global Journal of Environmental Science and Management, 10*(SI), 89–104.
4. Firdaus, H., Hardono, L. W., & Endramanto, V. (2024). Future Green Energy Circular Economy for Reaching Energy Transition in Indonesia: Case Study Biomass & Biogas Power Plant Using Palm Oil Plant in PT PLN Riau & Riau Islands. *ICT-PEP 2024 - International Conference on Technology and Policy in Energy and Electric Power: Resilient Power Systems: Navigating the Clean Energy Transition, Proceedings,* 503–510.
5. Mansur, D., Purba, W. L. I., & Takahasi, A. P. D. (2026). Upcycling of palm fronds and expanded polystyrene waste for producing liquid fuels with enhanced octane rating. *Sustainable Chemistry for Climate Action, 8.*
6. Ng, W. P. Q., Ang, X. T., & Lam, H. L. (2025). Optimising the sustainable circular economy of palm oil biomass with a P-graph approach to waste-to-wealth solutions. *Discover Sustainability, 6*(1).
7. Suhartini, S., Hidayat, N., Rohma, N. A., Paul, R., Pangestuti, M. B., Utami, R. N., ... & Melville, L. (2022). Sustainable strategies for anaerobic digestion of oil palm empty fruit bunches in Indonesia: a review. International Journal of Sustainable Energy, 41(11), 2044-2096.
8. Jaulis-Cancho, J. C., Morales, J. J., Varillas, A. M., Molina, M. A. B., Rojas, E. R. A., & Navarro, E. L. F. (2025). Biological efficiency of Pleurotus ostreatus cultivated in oil palm bagasse. *Acta Agronomica, 73*(3), 233–241.
9. Mohd Idris, M. N., Leduc, S., Yowargana, P., Hashim, H., & Kraxner, F. (2021). Spatio-temporal assessment of the impact of intensive palm oil-based bioenergy deployment on cross-sectoral energy decarbonization. *Applied Energy, 285,* 116460.
10. Leite, R. D. C., Lucheta, A. R., Holanda, R. B., Silva, P. M. P., Carmo, A. L. V. D., Leite, R. D. C., Melo, C. C. A. D., Costa, R. V. D., Montini, M., & Fernandes, A. R. (2022). Bauxite residue valorization — Soil conditioners production through composting with palm oil mill residual biomass. *Science of the Total Environment, 835.*
11. Rachmadona, N., Kahar, P., Juanssilfero, A. B., Nurrusyda, F. S., Dewi, D. A. S. L. A., Kurnia, I., Rahayu, I., & Ogino, C. (2024). Evaluation of lipid production efficiency using palm oil mill effluent as a carbon source by Lipomyces starkeyi. *Biomass Conversion and Biorefinery.*
12. Idris, M. N. M., & Hashim, H. (2021). Renewable energy transformation in Malaysia through bioenergy production: Policy insights from spatially-explicit modeling. In *Value-Chain of Biofuels: Fundamentals, Technology, and Standardization* (pp. 535–552).
13. Singh, S., Nara, R., Yadav, M., Sharma, C., Agrawal, S., & Kumar, A. (2025). Oil palm biomass: a potential feedstock for lignocellulolytic enzymes and biofuels production. *Environmental Science and Pollution Research, 32*(19), 11791–11814.
14. Goh, K. C., Kurniawan, T. A., AlSultan, G. A., Othman, M. H. D., Anouzla, A., Aziz, F., & Shafii, H. (2025). Innovative circular bioeconomy and decarbonization approaches in palm oil waste management: A review. *Process Safety and Environmental Protection, 195,* 106746.
15. Muryanto, M., Maryana, R., Triwahyuni, E., Sudiyani, Y., & Gozan, M. (2022). Furfural production using aqueous deep eutectic solvent. *AIP Conference Proceedings, 2708.*
16. Srivastava, R. K., Nedungadi, S. V, Akhtar, N., Sarangi, P. K., Subudhi, S., Shadangi, K. P., & Govarthanan, M. (2023). Effective hydrolysis for waste plant biomass impacts sustainable fuel and reduced air pollution generation: A comprehensive review. *Science of the Total Environment, 859.*
17. Quayson, E., Amoah, J., Rachmadona, N., Morita, K., Darkwah, L., Hama, S., & Ogino, C. (2020). Valorization of palm biomass waste into carbon matrices for the immobilization of recombinant Fusarium heterosporum lipase towards palm biodiesel synthesis. *Biomass and Bioenergy, 142,* 105768.
18. Vega-Quezada, C., Blanco, M., & Romero, H. (2017). Synergies between agriculture and bioenergy in Latin American countries: A circular economy strategy for bioenergy production in Ecuador. *New Biotechnology, 39,* 81–89.
19. Hassan, M. A., Farid, M. A. A., Zakaria, M. R., Ariffin, H., Andou, Y., & Shirai, Y. (2024). Palm oil expansion in Malaysia and its countermeasures through policy window and biorefinery approach. *Environmental Science \& Policy, 153,* 103671.
20. Hamid, Z. A. A., Razis, A. F. A., Mhd Ramle, S. F., & Yee Ching, W. (2025). Sustainable nutrient recovery from palm oil mill effluent through microalgae cultivation. In *Nutrients and Colored Compounds in Wastewater: Advanced Treatment and Recovery* (pp. 145–156).
21. Zulkarnain, M. Z. M., Nizam, A. A. H., Makhtar, M. M. Z., Shukor, H., & Yaser, A. Z. (2025). The Way Forward for Emerging Trends and Innovations in Biomass Processing for Circular Economy. In *Biomass Processing for Sustainable Circular Economy* (pp. 271–278).
22. Sathish Kumar, R. K., Sasikumar, R., & Dhilipkumar, T. (2024). Exploiting agro-waste for cleaner production: A review focusing on biofuel generation, bio-composite production, and environmental considerations. *Journal of Cleaner Production, 435.*
23. Gaur, V. K., Sharma, P., Sirohi, R., Varjani, S., Taherzadeh, M. J., Chang, J.-S., Yong Ng, H., Wong, J. W. C., & Kim, S.-H. (2022). Production of biosurfactants from agro-industrial waste and waste cooking oil in a circular bioeconomy: An overview. *Bioresource Technology, 343.*
24. Foong, S. Y., Chan, Y. H., Lock, S. S. M., Chin, B. L. F., Yiin, C. L., Cheah, K. W., Loy, A. C. M., Yek, P. N. Y., Chong, W. W. F., & Lam, S. S. (2023). Microwave processing of oil palm wastes for bioenergy production and circular economy:

Recent advancements, challenges, and future prospects. *Bioresource Technology, 369.*
25. Harahap, F., Silveira, S., & Khatiwada, D. (2019). Cost competitiveness of palm oil biodiesel production in Indonesia. Energy, 170, 62-72.
26. Boonsawang, P., & Youravong, W. (2017). Sustainability Issues, Challenges and Controversies Surrounding the Palm Oil Industry. In *Sustainability Challenges in the Agrofood Sector* (pp. 596–615).
27. Hoo, P. Y., Hashim, H., & Ho, W. S. (2020). Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff. *Journal of Cleaner Production, 270.*
28. Kushairi, A., Loh, S. K., Azman, I., Hishamuddin, E., Ong-Abdullah, M., Izuddin, Z. B. M. N., Razmah, G., Sundram, S., & Parveez, G. K. A. (2018). Oil palm economic performance in Malaysia and r&d progress in 2017. *Journal of Oil Palm Research, 30*(2), 163–195.
29. Aziz, N. I. H. A., Hanafiah, M. M., Gheewala, S. H., & Ismail, H. (2020). Bioenergy for a cleaner future: A case study of sustainable biogas supply chain in the Malaysian Energy Sector. *Sustainability (Switzerland), 12*(8).
30. Cheah, W. Y., Siti-Dina, R. P., Leng, S. T. K., Er, A. C., & Show, P. L. (2023). Circular bioeconomy in palm oil industry: Current practices and future perspectives. *Environmental Technology \& Innovation, 30,* 103050.
31. Purnama, I., Mutamima, A., Sunarno, S., Nasution, I. A. U., Syaputra, E., & Aziz, M. (2025). Scalable biochar production from oil palm fronds and waste cooking oil: Techno-economic and policy-oriented evaluation for rural deployment. *Journal of Cleaner Production, 527.*
32. Yashim, M. M., Mohammad, M., Baki, N. A., Asim, N., & Fudholi, A. (2023). IMPACT OF CARBOXYMETHYLATION PRETREATMENT ON THE MORPHOLOGICAL AND THERMAL CHARACTERISTICS OF CELLULOSE MICROFIBRILS FROM OIL PALM FROND TOWARD SOLAR THERMAL BENEFITS. *Cellulose Chemistry and Technology, 57*(3–4), 263–279.
33. Kurniawan, M. P., Guritno, A. D., Purwantana, B., & Supartono, W. (2020). Production cost approach and material flow cost accounting as a step towards increasing responsibility, efficiency, and sustainability (RES): The case of palm oil mill in Banten Indonesia. *IOP Conference Series: Earth and Environmental Science, 425*(1).
34. Sharma, R., & Lamsal, B. P. (2025). Understanding Bio-Based Surfactants, Their Production Strategies, Techno-Economic Viability, and Future Prospects of Producing Them on Sugar-Rich Renewable Resources. *Processes, 13*(9).
35. Nor Azam, N. A. M., Min, C. H., Nafchi, A. M., Abdullah, N. H., & Abdullah, W. N. W. (2025). Extraction and Physicochemical Characterization of Microcrystalline Cellulose from Oil Palm Empty Fruit Bunches. *Malaysian Journal of Chemistry, 27*(4), 95–104.
36. Ahmad Parveez, G. K., Kamil, N. N., Zawawi, N. Z. I. N., Ong-Abdullah, M., Rasuddin, R., Loh, S. K., Selvaduray, K. R., Hoong, S. S. O. I., & Idris, Z. (2022). OIL PALM ECONOMIC PERFORMANCE IN MALAYSIA AND R&D PROGRESS IN 2021. *Journal of Oil Palm Research, 34*(2), 185–218.
37. Ghara, M., Kumari, S., Jain, R., Mahar, H., Khanna, T., Jeyaseelan, C., & Paul, D. (2025). Microbial Alchemy: Waste valorization for yeast oil production for a circular future. *Current Trends in Biotechnology and Pharmacy, 19*(3A), 155–169.
38. Channei, D., Jannoey, P., Thammaacheep, P., Khanitchaidecha, W., & Nakaruk, A. (2025). From Waste to Value: Banana-Peel-Derived Adsorbents for Efficient Removal of Polar Compounds from Used Palm Oil. *Applied Sciences (Switzerland), 15*(4).
39. Ayompe, L. M., Nkongho, R. N., Acobta, A. N., Masso, C., & Egoh, B. N. (2025). Transforming palm oil production: sustainable techniques and waste management strategies for Cameroon's smallholder farmers. *Frontiers in Sustainable Food Systems, 9.*
40. Kushairi, A., Ong-Abdullah, M., Nambiappan, B., Hishamuddin, E., Bidin, M., Ghazali, R., & Parveez, G. K. A. (2019). Oil palm economic performance in Malaysia and R&D progress in 2018. *Journal of Oil Palm Research, 31*(2), 165–194.
41. Yeo, J. Y. J., How, B. S., Teng, S. Y., Leong, W. D., Ng, W. P. Q., Lim, C. H., & Lam, H. L. (2020). Synthesis of sustainable circular economy in palm oil industry using graph-theoretic method. *Sustainability, 12*(19), 8081.
42. Usapein, P., Tuntiwiwattanapun, N., Polburee, P., Veerakul, P., Seekao, C., & Chavalparit, O. (2022). Transition Pathway Palm Oil Research Framework toward a Bio-circular-green Economy Model using SWOT analysis: a case study of Thailand. *Frontiers in Environmental Science, 10,* 877329.
43. Mora-Villalobos, J.-A., Aguilar, F., Carballo-Arce, A.-F., Vega-Baudrit, J.-R., Trimino-Vazquez, H., Villegas-Peñaranda, L. R., Stöbener, A., Eixenberger, D., Bubenheim, P., Sandoval-Barrantes, M., & Liese, A. (2023). Tropical agroindustrial biowaste revalorization through integrative biorefineries—review part I: coffee and palm oil by-products. *Biomass Conversion and Biorefinery, 13*(2), 1469–1487.
44. Cazier, E. A., Pham, T.-N., Cossus, L., Abla, M., Ilc, T., & Lawrence, P. (2024). Exploring industrial lignocellulosic waste: Sources, types, and potential as high-value molecules. *Waste Management, 188,* 11–38.
45. Utami, A. R. I., Suwandi, S., Mustafa, Y. A., & Mel, M. (2021). Physical treatment of Oil palm Shell for briquette production as bioenergy at remote area. *E3S Web of Conferences, 226.*
46. Harahap, F. (2021). Bioenergy Sustainable development in Indonesia and its relation with SDGs goal. *IOP Conference Series: Earth and Environmental Science, 753*(1).
47. Anggala, T., & Simamora, B. H. (2025). Valorization of Spent Bleaching Earth Using Material Flow Analysis and Operational Root Cause Diagnostics. *IOP Conference Series: Earth and Environmental Science, 1564*(1).
48. Olabi, A. G., Shehata, N., Sayed, E. T., Rodriguez, C., Anyanwu, R. C., Russell, C., & Abdelkareem, M. A. (2023). Role of microalgae in achieving sustainable development goals and circular economy. *Science of the Total*

Environment, 854.
49. Pant, M., & Pant, T. (2023). Maximising biotransformation of pine needles to microbial lipids using Lipomyces starkeyi MTCC 1400T. *Renewable Energy, 206,* 574–581.
50. Sulin, S. N., Mokhtar, M. N., Baharuddin, A. S., & Mohammed, M. A. P. (2025). Simulation and techno-economic evaluation of integrated palm oil mill processes for advancing a circular economy. *Cleaner Environmental Systems, 19.*
51. Mohammadhosseini, H., Alyousef, R., & Tahir, M. M. (2021). RETRACTED: Towards Sustainable Concrete Composites through Waste Valorisation of Plastic Food Trays as Low-Cost Fibrous Materials. *Sustainability (Switzerland), 13*(4), 1–23.
52. Nagime, P. V, Chidrawar, V. R., Singh, S., Shafi, S., & Singh, S. (2025). Palm oil mill waste: A review on ecological improvement goals advancement and prospects. *Food and Humanity, 5.*
53. Zainal, A., Harun, R., & Idrus, S. (2022). Performance Monitoring of Anaerobic Digestion at Various Organic Loading Rates of Commercial Malaysian Food Waste. *Frontiers in Bioengineering and Biotechnology, 10.*
54. Bejarano, P. A. C., Rodriguez-Miranda, J. P., Maldonado-Astudillo, R. I., Maldonado-Astudillo, Y. I., & Salazar, R. (2022). Circular economy indicators for the assessment of waste and by-products from the palm oil sector. *Processes, 10*(5), 903.
55. Abdullah, M. A., Nazir, M. S., Hussein, H. A., Shah, S. M. U., Azra, N., Iftikhar, R., & Hung, Y. T. (2024). New perspectives on biomass conversion and circular economy based on Integrated Algal-Oil Palm Biorefinery framework for sustainable energy and bioproducts co-generation. *Industrial Crops and Products, 213,* 118452.
56. Budinarta, W., Ajijah, N., & Hermosaningtyas, A. A. (2025). Waste-to-Resource Strategies: The Potential of Agro-Industrial Residues for Microalgal Bioproducts in Indonesia. *Phycology, 5*(4).
57. Hamzah, M. A. A. M., Yusof, N., Zaini, M. A. A., Zakaria, Z. A., Jaafar, J., & Misdan, N. (2025). Advancing Heavy Metal Removal from Industrial Wastewater Using Oil Palm Waste–Based Adsorbent: toward Efficient Adsorption and Commercialization. *Current Pollution Reports, 11*(1).
58. Piastrellini, R., Rótolo, G. C., Arena, A. P., Civit, B. M., & Curadelli, S. (2024). Evaluation of the environmental sustainability of agricultural production using the methodologies of emergy analysis and life cycle assessment. Case study, tomato grown in Mendoza (Argentina). *Cleaner and Circular Bioeconomy, 8s.*
59. Ardhiansyah, H., Kusumaningrum, M., Bahlawan, Z. A. S., Prasetiawan, H., Savanti, F., & Fauziyyah, H. A. (2024). Green Pretreatment Techniques for Enhanced Delignification of Lignocellulosic Biomass: A Case Study of Biomass Waste in Indonesia. *IOP Conference Series: Earth and Environmental Science, 1381*(1).
60. de Carvalho, J. C., Molina-Aulestia, D. T., Martinez-Burgos, W. J., Karp, S. G., Manzoki, M. C., Medeiros, A. B. P., Rodrigues, C., Scapini, T., Vandenberghe, L. P. D. S., Vieira, S., Woiciechowski, A. L., Soccol, V. T., & Soccol, C. R. (2022). Agro-Industrial Wastewaters for Algal Biomass Production, Bio-Based Products, and Biofuels in a Circular Bioeconomy. *Fermentation, 8*(12).
61. Mohammadhosseini, H., Ngian, S. P., Alyousef, R., & Tahir, M. M. (2021). Synergistic effects of waste plastic food tray as low-cost fibrous materials and palm oil fuel ash on transport properties and drying shrinkage of concrete. *Journal of Building Engineering, 42.*
62. Rishanty, A., Sambodo, M. T., Silalahi, M., & Hambali, E. (2024). Zero-waste bioenergy to lower energy transition risks in Indonesia—a circular economy practice on methane capture in biogas production from POME. *BioEnergy Research, 17*(3), 1930–1942.
63. Bhagaskara, A., Trisunaryanti, W., Wijaya, K., Meylida Tazkia, A., Adi Saputra, D., Marantha Haryanto, V., Arfiana, A., & Zainuddin, I. (2026). Valence state-dependent catalytic behavior of Ni and Co in NiCo/activated carbon derived from spent Li-ion batteries for biojet fuel production. *Journal of the Indian Chemical Society, 103*(2).
64. Yaacob, J. S., Sheba, M., Lee, G. C., Abdullah, R., Rusli, L. S., Fariduddin, Q., ... & Mohd Rosli, N. S. (2026). Circular economy in action: palm oil kernel biochar and boiler ash enhance growth of Amaranthus viridis via ROS-induced antioxidants modulation. *Environmental Science and Pollution Research,* 1-20.
65. Rajakal, J. P., Hwang, J. Z. H., Hassim, M. H., Andiappan, V., Tan, Q. T., & Ng, D. K. (2023). Integration and optimisation of palm oil sector with multiple-industries to achieve circular economy. *Sustainable Production and Consumption, 40,* 318-336.
66. Promraksa, A., Seekao, N., Mueanmas, C., Chungsiriporn, J., & Rakmak, N. (2025). Synergistic Co-Pyrolysis of biomass for renewable energy: Enhanced energy recovery and heat integration from non-condensable gases. *Energy Conversion and Management, 343,* 120260.
67. Derman, E., Abdulla, R., Marbawi, H., & Sabullah, M. K. (2018). Oil palm empty fruit bunches as a promising feedstock for bioethanol production in Malaysia. *Renewable Energy, 129,* 285–298.
68. Rueda, C., Ponce, S., & Murillo, H. (2024). Techno-economic Analysis for the Valorization of Palm Kernel Shell via Hydrothermal Carbonization and Anaerobic Digestion. *Green Energy and Technology,* 177–196.
69. Loh, S. K., Lai, M. E., & Ngatiman, M. (2019). Vegetative growth enhancement of organic fertilizer from anaerobically-treated palm oil mill effluent (POME) supplemented with chicken manure in food-energy-water nexus challenge. *Food and Bioproducts Processing, 117,* 95–104.
70. Salehmin, M. N. I., Tiong, S. K., Mohamed, H., Zainal, B. S., Lim, S. S., Yasin, N. H. M., & Zakaria, Z. (2024). Sustainable bioenergy from palm oil mill effluent: Advancements in upstream and downstream engineering with techno-economic and environmental assessment. *Journal of Industrial and Engineering Chemistry, 133*, 122–147.
71. Abdulla, R., Derman, E., Balasubramaniam, S., Gansau, J. A., & Chandel, A. K. (2025). Bioconversion of Oil Palm

Empty Fruit Bunches into Lactic Acid via Lactobacillus acidophilus. *Waste and Biomass Valorization, 16*(9), 4955–4967.
72. Soleh, A., Saisahas, K., Samoson, K., Promsuwan, K., Saichanapan, J., Wangchuk, S., Somapa, N., Somapa, D., & Limbut, W. (2025). Revolutionizing oil palm biomass into laser-induced graphene for sustainable and high-performance electrochemical sensors. *Materials Today Chemistry, 47.*
73. Fukuda, S. (2020). Agricultural and Municipal Waste Management in Thailand. *In An Introduction to Circular Economy* (pp. 303–324).
74. Suhartini, S., Rohma, N. A., Mardawati, E., Hidayat, N., & Melville, L. (2022). Biorefining of oil palm empty fruit bunches for bioethanol and xylitol production in Indonesia: A review. *Renewable and Sustainable Energy Reviews, 154,* 111817.
75. Kongto, P., Palamanit, A., Pattiya, A., Promsampao, N., Sonsupap, S., Phusunti, N., Theapparat, Y., Chanakaewsomboon, I., & Tippayawong, N. (2025). Yields and characteristics of bio-oil and biochar from fast pyrolysis and co-pyrolysis of oil palm biomass using innovative twin screw reactor for bio-circular-green economy approach. *Biomass Conversion and Biorefinery, 15*(11), 17535–17552.
76. Martinez-Burgos, W. J., Bittencourt Sydney, E., Bianchi Pedroni Medeiros, A., Magalhães, A. I., de Carvalho, J. C., Karp, S. G., Porto de Souza Vandenberghe, L., Junior Letti, L. A., Thomaz Soccol, V., de Melo Pereira, G. V, Rodrigues, C., Lorenci Woiciechowski, A., & Soccol, C. R. (2021). Agro-industrial wastewater in a circular economy: Characteristics, impacts and applications for bioenergy and biochemicals. *Bioresource Technology, 341.*
77. Tun, M. M., Juchelkova, D., Win, M. M., Thu, A. M., & Puchor, T. (2019). Biomass energy: An overview of biomass sources, energy potential, and management in Southeast Asian countries. *Resources, 8*(2).
78. Amara, N. I., Chukwuemeka, E. S., Obiajulu, N. O., & Chukwuma, O. J. (2023). Yeast-driven valorization of agro-industrial wastewater: an overview. *Environmental Monitoring and Assessment, 195*(10).
79. Loon, L. K., Shukery, M. F., & Hashim, N. (2024). MILP model for optimal operation of biomass facility treatment for efficient oil palm biomass management. *Clean Technologies and Environmental Policy, 26*(6), 2007–2019.