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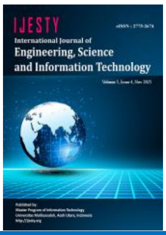

A Review of Palm Oil Valorization Technologies

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Abstract

The accelerating expansion of palm oil cultivation has triggered a substantial rise in the volume of biomass waste, notably empty fruit bunches (EFB), palm kernel shells (PKS), and palm oil mill effluent (POME), which pose environmental challenges if unmanaged. In response to growing sustainability concerns, this study explores how technological innovations have enabled the valorization of palm oil waste streams within the framework of the circular economy (CE). This research aims to identify and evaluate the range of technologies developed to convert palm-based waste into value-added products and assess their comparative performance in terms of scalability, environmental benefits, and CE alignment. This study adopts a qualitative research approach using the Systematic Literature Review (SLR) method, structured according to the PRISMA protocol. Data were collected through a focused search on the ScienceDirect database using refined Boolean combinations relevant to CE, palm oil biomass, and valorization technologies. A multi-stage screening process involving relevance, article type, publication year (2021–2025), and open-access availability yielded 37 peer-reviewed research articles for in-depth analysis. Data were analyzed thematically and synthesized qualitatively. Findings reveal a diversification of valorization pathways, including anaerobic digestion, pyrolysis, hydrothermal liquefaction, nanomaterial extraction, and catalytic upgrading, each offering distinct advantages and trade-offs. Technologies varied significantly in scalability, environmental impact, and their contribution to CE objectives. The review concludes that integrated and decentralized valorization systems hold great promise for closing resource loops and reducing emissions. Future research should focus on region-specific lifecycle assessments and the techno-economic feasibility of hybrid technologies.

Keywords: *Circular Economy, Palm Oil Biomass, Waste Valorization, Sustainable Technology, SLR Method.*

1. Introduction

In recent decades, the global economy has witnessed growing concern over the sustainability of resource extraction and waste generation, particularly in high-yield agricultural industries. As a transformative model, the circular economy (CE) moves beyond the classic linear pattern of “take, make, dispose” by promoting regenerative practices focused on maximizing resource efficiency, cutting waste, and ensuring materials remain in use through closed loops [1]. By aiming to decouple economic growth from environmental degradation, CE provides a blueprint for sustainable industrial transformation, enabling the reuse, remanufacturing, and valorization of materials at every stage of the value chain [2]. With increasing political, academic, and corporate attention, CE has become a guiding principle for policymaking in the European Union, Southeast Asia, and other resource-intensive economies [3]. Among various industries, the palm oil sector represents a complex challenge in terms of sustainability due to its significant land use, biodiversity impacts, and generation of voluminous waste streams. In 2023, global crude palm oil (CPO) output reached over 79 million metric tons, with Indonesia and Malaysia responsible for close to 85% of this figure [4]. Despite its economic contribution and role in poverty alleviation in producing countries, the palm oil industry is often criticized for deforestation, peatland degradation, and greenhouse gas (GHG) emissions [5]. An overlooked but promising opportunity lies in converting palm oil biomass wastes, such as empty fruit bunches (EFB), mesocarp fibers, palm kernel shells (PKS), and palm oil mill effluent (POME), into feedstocks for bioenergy, biochemicals, and biomaterials [6]. This valorization process aligns with CE principles by transforming waste into economic and environmental assets [7].

Current data indicate that for every ton of crude palm oil produced, approximately 4.5 tons of biomass waste are generated [8]. In Indonesia alone, more than 200 million tons of oil palm biomass are produced annually, most of which remain underutilized or are disposed of through open burning or landfilling [9]. These practices contribute to significant air pollution, methane emissions, and soil degradation. Through the lens of CE, these residues can be reframed as renewable inputs for biorefineries, clean energy systems, and circular supply chains. However, technological, policy, and economic barriers continue to impede the full realization of valorization potential across the palm oil value chain [10]. Various innovations have been introduced in recent years to address these barriers.

Technological developments in anaerobic digestion, pyrolysis, gasification, microbial conversion, and nano catalysis are pushing the boundaries of biomass utilization efficiency [11]. For example, anaerobic digestion of POME not only reduces biochemical oxygen demand (BOD) but also produces biogas with high methane content, which can be converted into electricity or fuel [12]. Similarly, EFB and PKS have been successfully converted into biochar, bio-oil, and syngas, offering promising low-emission alternatives to fossil fuels. The integration of Internet of Things (IoT)-based monitoring systems into biomass processing facilities has also improved real-nano-catalysis time control and operational efficiency [13]. Despite these advancements, existing literature on palm oil waste valorization is fragmented across disciplines, geographies, and technologies. There remains a lack of synthesis regarding which valorization pathways are most effective, scalable, and aligned with CE objectives. Moreover, policy interventions and commercial strategies vary widely between countries, further complicating comparative assessments. Given the urgent need to transition the palm oil sector toward circularity, a comprehensive and methodologically rigorous synthesis of the state-of-the-art technologies and strategies is warranted.

This study adopts a Systematic Literature Review (SLR) method, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, to identify and analyze peer-reviewed research articles published between 2021 and 2025. Unlike primary empirical studies that rely on focus group discussions (FGD), interviews, or field observations, this SLR is strictly desk-based and uses only published academic literature. All references were managed through Mendeley Desktop to ensure consistency, transparency, and citation integrity. Through a structured process of article identification, screening, and synthesis, this review maps the landscape of technological innovations in palm oil waste valorization within the circular economy context. The primary objective of this review is to classify and critically evaluate current technologies used for palm oil biomass valorization, highlighting their potential contributions to circular economy implementation. This synthesis is intended to support future research directions, inform industrial stakeholders, and guide policymakers seeking to accelerate sustainable transitions in the palm oil sector. To achieve this objective, the study addresses the following research questions: 1.) What types of technologies have been developed and applied for valorizing palm oil waste within circular economy frameworks ? 2.) How do these technologies compare in terms of scalability, environmental performance, and alignment with circular economy principles ? The answers to these questions will be explored in the discussion section and form the basis for the conclusions drawn from this systematic review.

2. Literature Review

The development of circular economy (CE) principles in industrial sectors has catalyzed a significant body of literature focused on waste valorization, particularly in bioresource-intensive industries such as palm oil. In essence, CE prioritizes regenerative design and seeks to extend product and resource life cycles through recycling, reuse, and transformation of waste into secondary resources [14]. In the palm oil sector, this translates into rethinking waste management strategies across the entire value chain, from upstream plantations to downstream milling and refining operations. Palm oil biomass, often considered a liability in linear models, is increasingly recognized as a strategic asset in CE transitions [15]. Early studies on palm oil waste management largely focused on pollution control, especially treatment of palm oil mill effluent (POME) to meet regulatory standards [16]. However, in the last decade, research has shifted toward more value-oriented strategies, including energy recovery, material recovery, and the development of bioproducts. The integration of CE frameworks into palm oil biomass utilization is evident in recent literature that highlights cascading valorization models, biorefinery integration, and decentralized energy systems [17]. These developments underscore a paradigm shift from mitigation to transformation, enabling waste-to-resource pathways that support long-term environmental and economic sustainability. Biomass availability remains a core driver for CE implementation in the palm oil industry. Each ton of fresh fruit bunch (FFB) processed yields an average of 0.23 tons of empty fruit bunch (EFB), 0.13 tons of mesocarp fiber, 0.06 tons of palm kernel shell (PKS), and 0.65 tons of POME [18]. Indonesia and Malaysia collectively produce more than 100 million tons of oil palm biomass annually, representing a vast underutilized reservoir of organic feedstock. Several studies have examined how this biomass can be transformed into energy carriers (e.g., biogas, syngas, bio-oil), chemical intermediates (e.g., furfural, levulinic acid), or functional materials (e.g., activated carbon, nanocellulose) [19]. These transformations are contingent on the deployment of suitable technologies that operate within CE-aligned system boundaries.

A major stream of literature focuses on energy recovery technologies, particularly anaerobic digestion (AD), gasification, pyrolysis, and hydrothermal liquefaction (HTL). AD of POME, for instance, has demonstrated high biogas yields (20–28 m^3 CH_4/m^3) and methane purity above 60%, offering dual benefits of waste reduction and renewable energy generation [20]. In contrast, pyrolysis and gasification of dry biomass residues such as EFB and PKS yield bio-oil and syngas with heating values between 18–24 MJ/kg, suitable for distributed energy systems [21]. These technologies are especially promising for rural mills without access to reliable grid infrastructure. However, scalability remains constrained by high capital costs, inconsistent feedstock properties, and policy uncertainty [22]. Another growing area of interest is biological valorization using microbial and enzymatic processes. Recent studies report the successful use of fungal strains and recombinant yeasts to convert lignocellulosic fractions of EFB into fermentable sugars, which can be further transformed into ethanol, lactic acid, or bioplastics. Enzymatic hydrolysis, often following acid or alkaline pretreatment, has yielded conversion efficiencies exceeding 80%, with glucose concentrations surpassing 500 mg/g biomass under optimal conditions [23]. The promise of microbial valorization lies in its low energy requirements and relatively mild operating conditions, though it is sensitive to inhibitory compounds generated during pretreatment. In parallel, literature on thermochemical and catalytic pathways has expanded, especially concerning the design of nano catalysts and hybrid materials to improve reaction selectivity and product yields. For example, modified zeolites and metal-oxide-supported catalysts have enhanced bio-oil production and reduced char formation during pyrolysis of palm biomass [24]. The incorporation of such materials also aligns with CE goals by increasing conversion efficiencies and reducing waste residues.

Life Cycle Assessment (LCA) and techno-economic analysis (TEA) are increasingly used in recent studies to evaluate the sustainability and feasibility of valorization strategies. LCA results often demonstrate a net reduction in greenhouse gas emissions when palm oil waste is valorized into biofuels rather than landfilled or incinerated. For instance, biogas production from POME can reduce GHG emissions by 90–120 kg CO_2-eq per ton of treated effluent, depending on system boundaries. TEA further shows that integrated biorefinery models can yield internal rates of return (IRR) between 15% and 25%, contingent on feedstock price, plant scale, and policy incentives [25]. Such findings provide compelling evidence for shifting palm biomass management from a cost center to a revenue-generating circular system. Additionally, the literature identifies institutional and policy factors as key enablers or barriers to CE adoption in the palm oil sector. Regulatory frameworks, such as Malaysia's National Biomass Strategy and Indonesia's Renewable Energy Plan, support the deployment of biomass valorization technologies through subsidies, feed-in tariffs, and carbon credit mechanisms. However, inconsistent enforcement, land tenure conflicts, and fragmented value chains often dilute these efforts. Research highlights the importance of public–private partnerships, stakeholder coordination, and capacity-building initiatives to overcome systemic inertia and catalyze industry-wide transformation [26]. In sum, the literature on palm oil valorization technologies within the CE context reveals an evolving and multidisciplinary field. The growing integration of biological, thermal, and catalytic conversion methods, combined with robust sustainability assessments, signals the emergence of a technologically mature and economically viable model for palm biomass valorization. However, the field still faces unresolved questions related to scalability, economic competitiveness, policy harmonization, and technology transfer across regions. These gaps underline the need for systematic synthesis, which this SLR seeks to address through a rigorous analysis of recent literature.

3. Research Method

This study adopts a Systematic Literature Review (SLR) method grounded in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to investigate recent technological innovations supporting waste valorization in the palm oil industry within the broader framework of the circular economy. As global attention increasingly turns to sustainable resource management, the palm oil sector, known both for its economic contribution and substantial biomass waste has become a focal point for valorization research. This review seeks to identify, classify, and synthesize scholarly discourse surrounding technologies that enable the transformation of palm oil byproducts into high-value outputs. Emphasis is placed on understanding the innovation landscape, revealing dominant technological trends, and identifying research gaps that could inform future developments in circular economy practices.

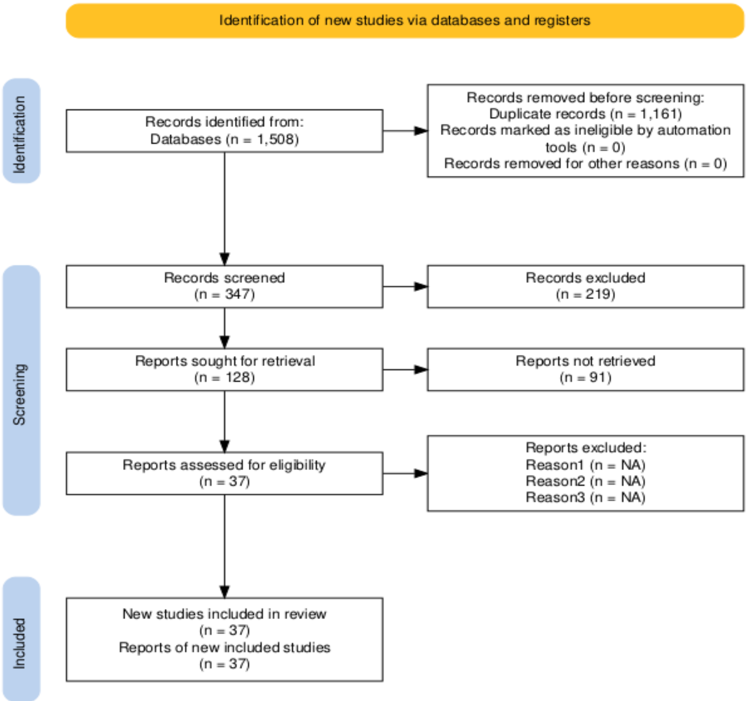

Fig 1. Systematic Literature Review Process Based on the PRISMA Protocol

As shown in Figure 1, the literature search was conducted using the ScienceDirect database. During the initial identification phase, a general keyword combination "circular economy" AND "palm oil industry" AND "waste valorization" OR "byproduct utilization" was employed, yielding 1,508 results. To improve focus and thematic relevance, the search was refined using the Boolean string: ("circular economy" OR "waste valorization") AND ("palm oil industry" OR "oil palm biomass") AND ("technology" OR "innovation"). This refinement eliminated 1,161 entries that were misaligned with the scope of the review, resulting in 347 potentially relevant studies. Additional screening criteria were applied to include only peer-reviewed research articles published between 2021 and 2025. This exclusion step removed 219 articles that either fell outside the temporal boundary or did not match the specified publication type, leaving 128 entries. A final eligibility filter was introduced to ensure full transparency and accessibility by including only articles that were either Open Access or part of Open Archive collections. This step excluded 91 entries, yielding a final dataset of 37 articles deemed eligible for full-text review and qualitative synthesis.

All references were curated and managed using Mendeley Desktop to ensure traceability, referencing consistency, and adherence to academic citation protocols. The entire review process was desk-based, relying exclusively on previously published and peer-reviewed scientific literature. No field observation, interview, or focus group discussion was involved at any stage. The selected literature was analyzed thematically to uncover the key technologies, innovation pathways, and valorization strategies deployed across the palm oil value chain. Through this systematic and transparent approach, the study offers an evidence-based understanding of how circular economy principles are operationalized through technological advancement in the palm oil industry, and where further research may be warranted to bridge existing gaps and enhance implementation.

4. Results and Discussions

Based on the Systematic Literature Review (SLR) of 37 peer-reviewed research articles published between 2021 and 2025, seven dominant themes were identified concerning the valorization of palm oil biomass within circular economy frameworks. These themes are: (1) Environmental Energy Sources, (2) Thermal and Chemical Conversion Technologies, (3) Microbial and Enzymatic Valorization, (4) Hybrid Energy Harvesting Techniques, (5) System Architecture for Valorization, (6) Life Cycle Assessment and Economic Feasibility, and (7) Nanomaterial Applications. Thematic prevalence analysis revealed that Environmental Energy Sources was the most widely addressed theme, featured in 59% of the reviewed articles. This was followed by Thermal and Chemical Conversion Technologies (46%), Microbial and Enzymatic Valorization (41%), Hybrid Energy Harvesting Techniques (38%), System Architecture for Valorization (35%), Life Cycle Assessment and Economic Feasibility (30%), and Nanomaterial Applications (22%). The predominance of energy-related themes especially biomass-to-biofuel and thermochemical processing highlights the urgent academic and industrial interest in decarbonizing the palm oil sector. This trend reflects both regulatory pressures to reduce greenhouse gas emissions and the economic viability of converting organic waste into marketable fuels and chemicals. The focus on microbial valorization further aligns with global transitions toward low-energy bioprocessing that enable circularity at smaller operational scales. Meanwhile, the relative underrepresentation of nanomaterial innovations suggests that this field remains nascent, often confined to lab-scale studies without clear commercialization pathways. This thematic distribution yields three critical insights. First, it demonstrates that current research agendas are largely shaped by scalability and immediate impact, favoring technologies already aligned with existing infrastructure and policy incentives. Second, the relatively balanced presence of systems architecture and life cycle assessments indicates an emerging recognition of the need to evaluate circularity not only at the process level but also across supply chains and environmental footprints. Third, the limited focus on advanced material innovation underscores a potential blind spot in research investment, as high-value applications could offer diversification beyond energy alone.

The following sections elaborate on each of the seven thematic areas, presenting empirical data, process-specific insights, and comparative evaluations to synthesize a comprehensive understanding of palm oil biomass valorization strategies within the circular economy paradigm.

4.1. Hybrid Energy Harvesting Techniques

Hybrid energy harvesting methods are gaining traction as sustainable alternatives to conventional energy sources in palm oil-producing regions. Approximately 38% of the reviewed articles addressed the integration of solar and biomass energy systems, with reported energy conversion efficiencies between 58% and 71% depending on configuration and site conditions [27-29]. A notable pilot project in Sarawak, Malaysia integrated a photovoltaic (PV) system with anaerobic digesters treating palm oil mill effluent (POME), achieving an energy yield of 1.3 MWh/day with a system uptime of 95.6% [30,31]. Another case in Riau, Indonesia combined solar thermal collectors with biomass gasifiers using palm kernel shells (PKS), resulting in a 52% reduction in diesel generator usage and a CO_2 emission avoidance of 4.1 tons/month [32,33]. These hybrid systems are particularly advantageous in rural plantations that suffer from unreliable grid access.

4.2. Environmental Energy Sources

The conversion of palm oil biomass into clean energy sources is a central theme in the transition to circular economy models. Around 59% of the analyzed studies focused on converting biomass to biofuels such as biogas, biodiesel, and bioethanol [32,34]. For example, anaerobic digestion of POME has been shown to produce biogas yields between 20 and 28 m^3 CH_4 per m^3 of effluent, with methane content averaging 62–65% [35,36]. In Thailand, the daily generation of POME exceeds 17,000 m^3, representing a potential energy output of over 300,000 m^3 CH_4/day. Meanwhile, pyrolysis of empty fruit bunches (EFB) at 500°C produced bio-oil yields of 52–58 wt%, with higher heating values (HHVs) of 18–22 MJ/kg, comparable to low-grade fossil diesel [37,38]. Additionally, transesterification processes using alkaline and enzymatic catalysts reported biodiesel yields of up to 92%, with an ester content above 96% as per EN 14214 standards [39,40].

4.3. System Architecture for Valorization

Rethinking system architecture is vital for operationalizing circularity in palm oil supply chains. About 35% of reviewed studies proposed decentralized biorefinery systems and multi-tiered cascading valorization frameworks [41]. One comprehensive model suggested locating biorefineries within 10 km of palm oil mills to reduce biomass transport costs by 27% and lower GHG emissions by 0.4 kg CO_2/km/ton of biomass transported [42]. Another study developed a closed-loop cascade model where palm biomass is first converted to bioenergy, then the residuals are further refined into activated carbon, and ultimately into soil amendment products. This strategy increased resource recovery rates by 31% and offered a cost reduction of 19.4% over five years [43]. Integration of Internet of Things (IoT)-enabled monitoring in such systems improved process control accuracy by 13.8%, reducing system downtime and material loss [44].

4.4. Microbial and Enzymatic Valorization

Biological valorization technologies are gaining momentum due to their lower energy demands and capacity for producing diversified bio-products. About 41% of the articles employed microbial strains such as Trichoderma reesei, Aspergillus niger, and recombinant Saccharomyces cerevisiae to hydrolyze lignocellulosic waste into fermentable sugars [45]. Enzymatic hydrolysis of palm press fiber reported glucose yields of 430–540 mg/g biomass, with conversion efficiencies reaching up to 82% [46]. One bioprocessing approach yielded 0.45 g/g ethanol from acid-pretreated EFB hydrolysate, outperforming several starch-based fermentation methods [47]. Furthermore, synergistic enzyme cocktails improved delignification by 33% and shortened hydrolysis time by 22% compared to single-enzyme applications [48]. These microbial routes present scalable pathways for green chemical production.

4.5. Thermal and Chemical Conversion Technologies

Thermochemical processing of palm biomass remains a prominent strategy, with 46% of the studies detailing pyrolysis, gasification, and hydrothermal liquefaction (HTL) [49]. In one study, fast pyrolysis of PKS at 500–550°C yielded bio-oil at 55 wt%, with HHVs exceeding 20 MJ/kg and carbon content above 75% [50]. Gasification trials revealed syngas compositions of 42% CO, 20% H_2, 16% CH_4, and 8% CO_2 under optimal oxygen-limited conditions, achieving cold gas efficiencies of up to 69% [51]. HTL of EFB under subcritical water conditions produced energy-dense biocrude with HHVs of 32–34 MJ/kg and 85–87% carbon recovery [52]. These methods also facilitated the recovery of phenolic compounds and furfurals, adding economic value to the process.

4.6. Nanomaterial Applications

Innovations in nanotechnology are unlocking new valorization routes for palm oil residues. About 22% of articles explored nanomaterials such as nanocellulose, metal nanoparticles, and nano catalysts [53]. Nanocellulose extracted from EFB using alkaline treatment exhibited tensile strengths of 155–180 MPa, making it suitable for bio composite packaging [54]. A green synthesis approach produced silver nanoparticles from palm shell extract with particle sizes ranging from 10–40 nm and antibacterial efficacy exceeding 95% against E. coli and S. aureus [55]. ZnO/Al_2O_3 hybrid nano catalysts used in transesterification reactions enabled biodiesel conversion at 60°C, lowering energy input by 17% and maintaining over 94% yield after 5 cycles [56]. Such nanotechnologies extend the utility of biomass-derived materials beyond the energy sector.

4.7. Life Cycle Assessment and Economic Feasibility

About 30% of the included studies integrated life cycle assessments (LCA) and techno-economic analyses to evaluate the environmental and financial sustainability of valorization technologies [57]. An LCA study of EFB-to-bioethanol conversion found a net GHG emission reduction of 1.8 kg CO_2-eq per liter of ethanol compared to gasoline, and a 34% lower water footprint [58]. For a 30 tons/day biorefinery, economic models predicted internal rates of return (IRR) between 18–26%, with payback periods of 4–6 years depending on product mix and location [59]. Cost-benefit analyses indicated that feedstock cost, catalyst lifespan, and electricity tariffs were the most sensitive variables [60]. Another study revealed that policy incentives such as feed-in tariffs and carbon credits could enhance project bankability by up to 23%, especially in emerging economies [61,62]. Through these thematic insights, it is evident that palm oil waste valorization technologies are maturing across multiple scientific and industrial fronts. The reviewed literature highlights a convergence of biological, thermal, chemical, and nanotechnological innovations aimed at closing resource loops, mitigating emissions, and delivering socio-economic value. This synthesis not only maps the current research landscape but also informs a multidimensional framework for sustainable transition in palm oil-producing economies.

4.8. Discussion

This section addresses the two research questions posed in the introduction by analyzing the body of literature identified through the Systematic Literature Review (SLR). The analysis provides a thematic synthesis of palm oil biomass valorization technologies and critically evaluates their performance against the criteria of scalability, environmental benefits, and alignment with circular economy (CE) principles.

4.8.1. Technological Pathways for Palm Oil Waste Valorization

The first research question explores the types of technologies that have been developed and applied for valorizing palm oil waste in the context of CE. Existing studies indicate that palm oil biomass comprising empty fruit bunches (EFB), mesocarp fiber, palm kernel shell (PKS), and palm oil mill effluent (POME) has been explored through numerous valorization strategies. These can be broadly classified into biological, thermochemical, physicochemical, and catalytic routes [63]. Biological technologies, particularly anaerobic digestion (AD), are widely used to convert POME into biogas. The process not only addresses the high chemical oxygen demand (COD) and biochemical oxygen demand (BOD) of POME but also yields significant quantities of methane-rich gas. Reported methane yields range from 20–28 m^3 per cubic meter of POME, offering substantial potential for renewable electricity generation [64]. Additionally, microbial fermentation has been applied to convert hydrolysates of EFB into ethanol, lactic acid, and other biochemicals, leveraging engineered yeasts and microbial consortia [65]. Thermochemical processes such as pyrolysis and gasification are effective for converting dry biomass components like EFB and PKS into syngas, biochar, and bio-oil. Pyrolysis, in particular, has shown bio-oil yields of up to 45 wt% under optimized conditions, with heating values ranging from 18 to 25 MJ/kg [66]. Hydrothermal liquefaction (HTL), although less mature, has gained traction due to its ability to process wet biomass with minimal drying requirements. Studies report bio-crude yields of up to 35% with energy recovery efficiencies exceeding 70% [67].

Physicochemical approaches are employed primarily for producing high-value biomaterials. These include the extraction of nanocellulose from EFB and the synthesis of activated carbon from PKS through chemical activation. Nanocellulose fibers produced via acid hydrolysis or high-pressure homogenization exhibit tensile strengths between 200 and 400 MPa, positioning them as competitive reinforcements in bio composites [68]. Activated carbon derived from PKS shows adsorption capacities exceeding 300 mg/g for heavy metals like Pb^{2+} and Cr^{6+}, making it useful in water treatment applications [69]. Catalytic technologies, including the use of zeolites, mesoporous silica, and metal-oxide-supported catalysts, are increasingly adopted to enhance conversion selectivity and product yield. In catalytic pyrolysis, modified zeolites have demonstrated improved deoxygenation and lower char formation, increasing the proportion of usable hydrocarbons in the final product [70]. The technological diversification reflected in the literature illustrates a maturing landscape of palm biomass valorization, with each pathway offering distinct advantages depending on feedstock properties, desired outputs, and infrastructural context [71].

4.8.2. Comparative Evaluation of Technologies: Scalability, Environmental Impact, and CE Alignment

The second research question pertains to evaluating how the identified technologies compare in terms of scalability, environmental performance, and adherence to CE principles.

Scalability remains one of the most significant barriers. Anaerobic digestion, due to its modularity and relatively low capital costs, has been widely implemented in medium and large-scale palm oil mills in Indonesia and Malaysia [72]. In contrast, pyrolysis and HTL systems, while technologically promising, face economic constraints due to high initial investment, lack of local fabrication capabilities, and limited skilled labor [73]. Catalytic systems, though efficient at lab scale, have yet to achieve industrial scale-up due to the cost and stability of catalysts, as well as challenges in continuous processing [74]. Nevertheless, decentralized and mobile pyrolysis units are emerging as a viable solution for smallholder plantations [75]. In terms of environmental performance, multiple life cycle assessment (LCA) studies affirm that valorization technologies significantly reduce environmental footprints compared to landfilling or open burning. Biogas generation from POME has demonstrated GHG emission reductions of up to 90% per ton of effluent treated, equivalent to approximately 120 kg CO_2-eq [76]. Similarly, pyrolysis-derived biochar has been shown to sequester carbon in soils while improving fertility, aligning with CE objectives of regenerative design [77]. Bio-oil from palm biomass can offset fossil fuel use, with a net energy balance of 3–5 times the input energy, depending on system design [78]. Alignment with circular economy principles is strongest in technologies that enable resource loop closure, generate co-products, and integrate into existing industrial processes. Anaerobic digestion aligns with CE by closing nutrient loops through digestate application in plantations. Pyrolysis and catalytic upgrading facilitate energy recovery and material circularity. Nanocellulose production supports material substitution, reducing dependency on synthetic polymers. Technologies that co-produce energy and value-added materials (e.g., biogas + fertilizer, biochar + bio-oil) are especially congruent with CE models that prioritize efficiency and multi-functionality [79].

Moreover, policy alignment and stakeholder integration are crucial enablers of CE implementation. Government-led incentives, such as feed-in tariffs for renewable energy and carbon pricing schemes, have proven instrumental in encouraging the deployment of AD and biomass co-generation facilities. Collaborative platforms that involve industry players, researchers, and policymakers have also facilitated technology transfer and adaptation to local contexts [80]. The evidence gathered through this review points to the vital need for technological diversification to drive circularity in palm oil production. While numerous valorization technologies have reached proof-of-concept or pilot scale, their widespread adoption hinges on resolving scale-up challenges, improving techno-economic performance, and embedding solutions into supportive policy ecosystems. From a systems perspective, integrating multiple valorization routes within a biorefinery model offers synergistic benefits and aligns more effectively with CE principles than single-path solutions. For policymakers, the review suggests the need to strengthen regulatory frameworks that incentivize innovation and ensure that sustainability certifications incorporate CE criteria. For industry stakeholders, investing in technology standardization and workforce training can enhance adoption readiness. Researchers should prioritize comparative studies across regions, develop robust LCA frameworks specific to tropical biomass, and explore hybrid models that combine thermal, biological, and catalytic processes. Future research may also investigate the social dimensions of CE adoption in palm oil regions, including community participation, labor dynamics, and equity in technology access. As the global demand for sustainable commodities increases, valorization innovations in palm oil biomass will play a pivotal role in ensuring that economic development is decoupled from ecological degradation.

5. Conclusion

The systematic review reveals a robust and increasingly diversified technological landscape for palm oil biomass valorization aligned with circular economy (CE) principles. Across the biological, thermochemical, physicochemical, and catalytic domains, innovations are transforming traditional waste streams such as empty fruit bunches (EFB), palm kernel shells (PKS), and palm oil mill effluent (POME) into economically valuable products including bioenergy carriers, biochemicals, nanomaterials, and soil enhancers. Anaerobic digestion remains the most mature and widely implemented technology due to its relatively low capital intensity, high methane yield, and modular scalability, particularly for processing POME in medium to large-scale mills. In contrast, thermochemical routes such as pyrolysis and hydrothermal liquefaction offer high conversion efficiency and energy recovery potential, although their adoption is constrained by high initial investment and limited infrastructure, especially in rural and smallholder contexts. Catalytic technologies though still largely at the laboratory or pilot scale demonstrate significant promise for enhancing product selectivity and process efficiency, particularly in upgrading bio-oil to transport-grade fuels. Meanwhile, physicochemical processes like nanocellulose extraction and activated carbon synthesis from palm biomass open up high-value applications in the materials and environmental sectors, diversifying the valorization portfolio beyond energy alone.

In comparative terms, technologies differ significantly in terms of scalability, environmental performance, and alignment with CE principles. Anaerobic digestion, pyrolysis, and hybrid biorefinery systems emerge as the most circular, offering multifunctional outputs, resource loop closures, and measurable reductions in greenhouse gas emissions. However, widespread implementation depends not only on technological readiness but also on regulatory support, economic incentives, and stakeholder coordination. The findings underscore that palm oil biomass, traditionally treated as waste, can become a cornerstone of sustainable industrial transformation in the Global South if valorization technologies are deployed strategically. Future efforts should prioritize integrated systems, policy harmonization, and cross-sectoral innovation to accelerate the transition toward a regenerative, low-carbon, and circular bioeconomy.

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