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Review Article

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Benefits of Oil Palm Biomass

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ABSTRACT

Heightened global demand for clean energy sources has catalyzed the reassessment of agro-industrial residues, with oil palm biomass gaining recognition as a valuable input for circular bioeconomy development. Although it is widely available across Southeast Asia, with notable concentrations in Indonesia and Malaysia, the full range of technological, environmental, and economic benefits of oil palm biomass remains underexplored in a systematically synthesized form. This study aims to critically assess and consolidate scholarly findings on the valorization of oil palm biomass through a qualitative Systematic Literature Review (SLR). The research adopted the PRISMA framework, focusing exclusively on peer-reviewed, open-access articles published between 2023 and 2025, sourced from the ScienceDirect database. An initial dataset of 5,011 articles was filtered through multiple stages, resulting in 43 eligible publications. Data were extracted using thematic coding and analyzed through qualitative content analysis to identify recurring patterns, emerging themes, and knowledge gaps. The results indicate that oil palm biomass offers significant potential across three key dimensions: energy production (via pyrolysis, gasification, and biorefinery techniques), environmental enhancement (through carbon sequestration, waste minimization, and emission reduction), and economic viability (e.g., positive return on investment and local job creation). However, the utilization of this resource remains constrained by technological, logistical, and policy-related challenges. In conclusion, oil palm biomass presents a multifaceted opportunity for sustainable development. Future research is recommended to explore site-specific life cycle assessments, decentralized bioindustry models, and integrated policy frameworks.

Keywords: Oil Palm Biomass, Bioenergy, Systematic Literature Review, Sustainability, Valorization

Introduction

Amid rising energy demands and deepening environmental crises on a global scale, the pursuit of renewable and sustainable energy solutions has gained unprecedented importance. Mounting pressure to cut back on fossil fuel use, control emissions, and address the impacts of climate change has galvanized worldwide momentum toward building low-carbon economies. Energy demand worldwide is expected to rise by 25% between 2020 and 2040, according to forecasts from the International Energy Agency, with renewable sources predicted to contribute close to half of global electricity generation by 2050 [1]. Beyond its environmental rationale, this transition offers a significant socioeconomic prospect for countries in the Global South endowed with abundant biomass potential.

Among the various biomass sources, oil palm (Elaeis guineensis) stands out due to its vast global cultivation and substantial volume of biomass residues. Oil palm plantations, common in tropical countries like Indonesia, Malaysia, Thailand, and Nigeria, produce various biomass residues such as EFB, mesocarp fiber, PKS, fronds, and trunks. With the ongoing expansion of palm oil production, global oil palm plantations are projected to yield roughly 229 million tons of biomass annually, a number that is steadily rising [2]. Annually, Indonesia generates in excess of 90 million tons of biomass derived from oil palm, underscoring its substantial production capacity, offering immense potential for valorization into high-value products and renewable energy sources [3].

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Despite its historical association with deforestation and carbon emissions, the oil palm industry has gradually garnered attention for its potential role in sustainable development through the effective utilization of its biomass by-products. When appropriately managed, Oil palm biomass offers more than just a sustainable energy alternative; it also facilitates waste management, strengthens circular economy approaches, and supports socioeconomic progress in rural communities [4]. These benefits, however, are not automatically realized. They depend heavily on the technological, policy, and market frameworks that support biomass conversion and integration into energy systems.

Oil palm biomass can be harnessed in various forms, including direct combustion, gasification, pyrolysis, anaerobic digestion, and biochemical conversion. These processes enable the production of electricity, heat, biogas, bioethanol, biochar, bioplastics, and a variety of other industrial products. For instance, thermal conversion of empty fruit bunches has been shown to yield 3,800–4,200 kcal/kg of energy, comparable to low-grade coal, while biogas recovery from palm oil mill effluent (POME) can supply electricity to rural communities and offset fossil fuel consumption [5]. Moreover, advanced technologies such as co-firing and hybrid renewable systems further enhance the efficiency and environmental performance of oil palm biomass utilization [6].

Beyond energy applications, oil palm biomass holds promise for material innovation and sustainable agriculture. EFB and fronds, for instance, are increasingly used as raw materials in bio-composites, pulp and paper, organic fertilizers, and animal feed. This multifunctionality positions oil palm biomass as a keystone resource in both the bioeconomy and circular economy narratives. Studies have shown that converting just 10% of total oil palm biomass in Southeast Asia into value-added products could contribute more than USD 3 billion annually to regional economies [7].

However, the widespread adoption and valorization of oil palm biomass are not without challenges. Technological constraints, such as the high moisture content and heterogeneity of raw biomass, often lead to suboptimal energy conversion efficiencies. Additionally, logistical and infrastructure limitations, such as poor rural transportation networks and insufficient collection systems, hinder the economic viability of biomass-based energy projects in remote plantation areas [8]. Policy fragmentation, inconsistent incentives, and weak enforcement further exacerbate these issues, limiting private sector participation and investment in biomass development.

Moreover, sustainability concerns persist around the lifecycle impacts of oil palm biomass utilization. While energy recovery from waste streams like POME and EFB reduces methane emissions and landfilling, the environmental trade-offs of large-scale biomass harvesting such as soil nutrient depletion and biodiversity loss must be carefully managed. Consequently, integrated assessment frameworks that consider both environmental and socioeconomic parameters are crucial to ensure that biomass utilization supports broader sustainability goals rather than undermining them [9,10].

In light of these complexities, a comprehensive synthesis of existing literature is essential to map the current state of knowledge, identify gaps, and provide actionable insights for researchers, practitioners, and policymakers. Systematic Literature Review (SLR) offers a rigorous methodological approach to achieve this by systematically identifying, evaluating, and synthesizing empirical findings from peer-reviewed sources. By employing SLR methods based on the PRISMA framework, this study seeks to consolidate interdisciplinary perspectives on the benefits of oil palm biomass across energy, environmental, technological, and economic dimensions.

The initial literature search using the broad term "valorization of oil palm biomass" yielded 5,011 results from the ScienceDirect database. This was followed by a refined Boolean search using the keywords: “oil palm biomass” AND (energy OR bioenergy OR biofuel) AND (“renewable energy” OR “sustainable energy”) AND (benefits OR potential). After excluding 4,477 non-relevant articles, 534 results remained. Further filters limited the timeframe to publications from 2023 to 2025, resulting in 149 eligible articles. Accessibility screening reduced the dataset to 43 open-access, peer-reviewed publications for in-depth analysis. All references were managed using Mendeley Desktop, ensuring consistency and eliminating duplicates.

This study aims to systematically assess the multifaceted benefits of oil palm biomass as identified in current literature, with specific attention to its role in renewable energy generation, carbon footprint reduction, material innovation, and sustainable economic development. The ultimate goal is to provide an integrated understanding of how oil palm biomass can contribute meaningfully to global sustainability objectives while addressing the practical barriers to its implementation.

Accordingly, this article is guided by the following two research questions:

- What are the primary technological, environmental, and economic benefits of oil palm biomass as identified in recent scholarly literature?
- What are the key enablers and constraints affecting the effective utilization and valorization of oil palm biomass in real-world contexts?

These questions will be addressed in the Discussion section and further summarized in the Conclusion, forming the analytical backbone of this SLR-based investigation.

Literature Review

Scholarly discourse has increasingly highlighted oil palm biomass in recent years, recognizing its potential to support sustainable energy strategies, environmental preservation, and the development of rural economies. Generating the majority of the world’s palm oil supply, Indonesia and Malaysia produce a combined total exceeding 100 million tons of biomass each year, including EFB, PKS, mesocarp fibers, POME, and trunk waste, most of which remains largely untapped [11]. While oil palm plantations have expanded rapidly, this growth has also been accompanied by rising environmental concerns, particularly deforestation and ecosystem degradation, underscoring the need for sustainable waste valorization strategies.

A central theme in the literature revolves around the energy potential of oil palm biomass. Research indicates that the calorific value of oil palm shell reaches approximately 18.9 MJ/kg, making it competitive with conventional fossil fuels such as sub-bituminous coal [12]. Similarly, EFB can yield about 17 MJ/kg, though its high moisture content requires preprocessing such as torrefaction or drying to optimize combustion efficiency [13]. Studies have shown that co-firing oil palm biomass in conventional coal power plants can reduce CO_2 emissions by up to 40%, without major modifications to existing infrastructure.

Beyond its role in energy generation, oil palm biomass is also investigated for its potential as a feedstock in biofuel and biochemical production. Second-generation bioethanol derived from EFB and mesocarp fibers has attracted attention due to their low lignin content and high cellulose content [14]. Enzymatic hydrolysis and fermentation of EFB biomass using Saccharomyces cerevisiae and other engineered strains have demonstrated ethanol yields exceeding 270 L/ton of dry biomass [15]. Meanwhile, palm oil mill effluent has been used in anaerobic digestion systems for biogas production, with methane yields ranging from 20 to 28 m^3 per m^3 of POME, depending on operational parameters [16].

Another area of interest is the environmental implications of biomass valorization. Life Cycle Assessment (LCA) studies reveal that converting EFB into energy or bioproducts significantly reduces the carbon footprint compared to open dumping or field incineration. Furthermore, integrating biomass conversion facilities within palm oil mills facilitates closed-loop production systems, reducing waste discharge and water usage while increasing overall energy efficiency [17].

The literature also points to a growing focus on the techno-economic feasibility of oil palm biomass-based projects. Investment analyses indicate that small-to-medium scale biomass power plants (5–10 MW) can achieve an internal rate of return (IRR) of 12–18% over a 10-year horizon, particularly when government incentives such as feed-in tariffs or carbon credits are included [18]. However, several studies also highlight infrastructural, regulatory, and logistical challenges, such as insufficient biomass collection systems, a lack of standardization in feedstock quality, and inconsistent policy support.

Despite these challenges, technological innovations continue to emerge. Recent advancements in pyrolysis, gasification, and hydrothermal carbonization have improved conversion efficiencies while generating value-added products such as biochar and syngas. Biochar, in particular, is gaining attention for its potential use in soil remediation, carbon sequestration, and even in advanced applications such as energy storage materials [19]. These breakthroughs point toward an increasingly circular bioeconomy model centered around oil palm biomass.

Academic studies further examine the social and economic dimensions of biomass utilization. In rural areas, biomass-based enterprises offer employment opportunities, contribute to local value chains, and reduce dependence on imported fossil fuels. Moreover, community-scale biomass initiatives are being explored to empower smallholders and cooperatives, though successful implementation remains contingent on equitable access to resources and technical support [20].

From a policy standpoint, literature emphasizes the importance of institutional coherence, regulatory clarity, and incentive structures to support biomass valorization. Countries like Malaysia have introduced mandates for renewable energy mix targets and for reducing palm oil waste, although enforcement and coordination remain inconsistent. Policy fragmentation, particularly between the agricultural and energy sectors, often leads to underutilization of biomass potential. Thus, researchers call for integrated policy frameworks that align environmental, economic, and energy objectives.

In summary, the existing literature reveals a multidimensional landscape of oil palm biomass research. The identified themes include energy conversion technologies, biofuel and biochemical applications, environmental impact assessments, techno-economic analyses, policy frameworks, and socio-economic contributions. These findings serve as the analytical foundation of this Systematic Literature Review, which seeks to synthesize and critically evaluate the benefits of oil palm biomass utilization across environmental, technological, economic, and social dimensions.

Accordingly, the next sections of this article will build upon the established literature by systematically categorizing and analyzing the emerging themes from the 43 selected peer-reviewed sources. Through this, we aim to identify the prevailing benefits, constraints, and opportunities for oil palm biomass valorization, which will be discussed in depth and contextualized in relation to current global sustainability imperatives.

Method

This study employs the Systematic Literature Review (SLR) method, structured according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to systematically evaluate the academic discourse on the benefits and potential applications of oil palm biomass. As oil palm cultivation continues to dominate the agricultural landscape in many tropical regions, the vast volume of biomass residues generated, such as empty fruit bunches, mesocarp fibers, fronds, and palm kernel shells, has sparked growing interest among scholars and practitioners. Once regarded as mere waste, these residues are increasingly recognized for their potential to support sustainable energy transitions, environmental restoration, and economic valorization. Within the context of the global shift toward renewable energy and circular economies, oil palm biomass emerges as a strategic resource with multi-sectoral benefits.

Yet, despite its considerable promise, the utilization of oil palm biomass remains uneven, constrained by technological, policy, and market-related challenges. This review seeks to address these knowledge gaps by consolidating and critically analyzing peer-reviewed literature on the multifaceted benefits of oil palm biomass, particularly its role in advancing sustainable energy solutions, resource efficiency, and waste valorization. Through a transparent and replicable review process, this study synthesizes key findings from recent literature, offering a consolidated understanding of how oil palm biomass contributes to broader sustainability goals and highlighting areas for further research and policy development.

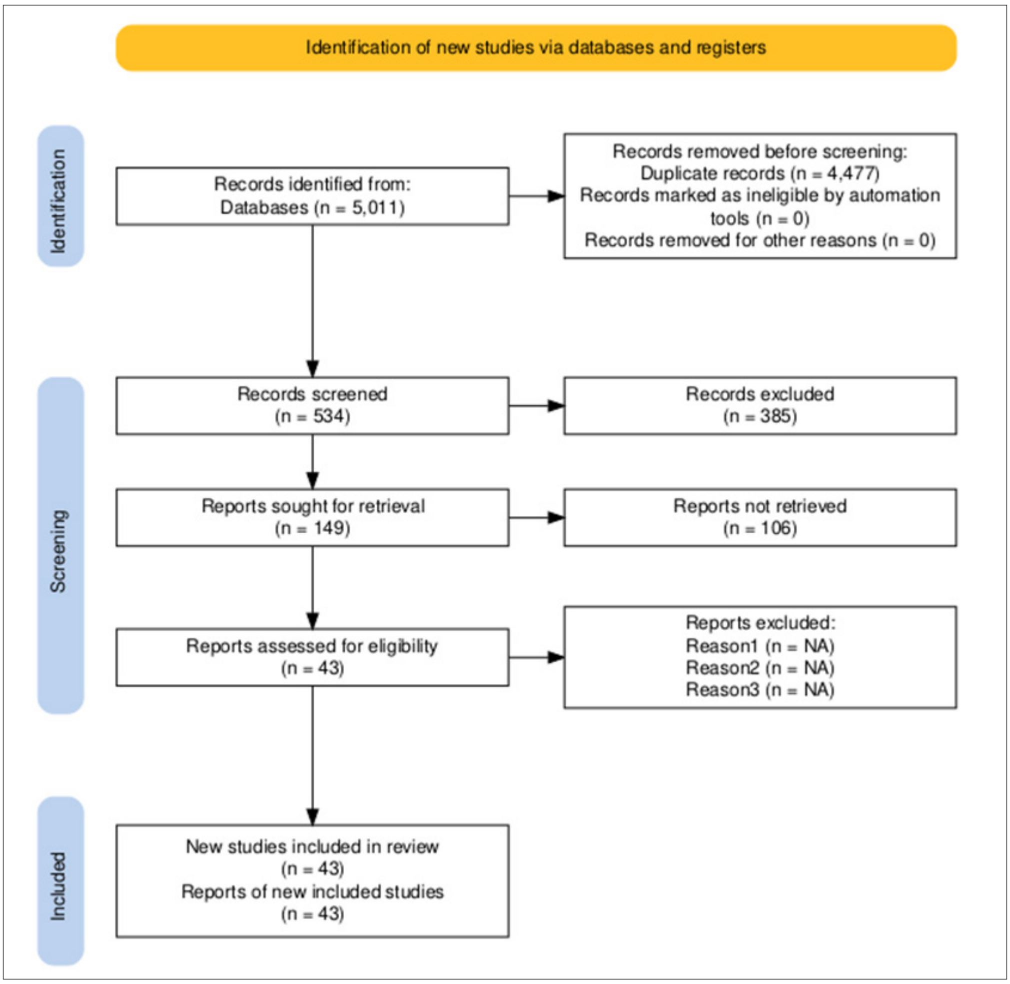

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 outlines the SLR process employed in this study, which comprises four main stages: identification, screening, eligibility, and final inclusion. The literature search was conducted exclusively through the ScienceDirect database due to its comprehensive coverage in environmental and energy-related research. The initial search used the broad keyword string "valorization of oil palm biomass," which yielded 5,011 articles. To enhance thematic precision and relevance, a refined Boolean query was applied: "oil palm biomass" AND (energy OR bioenergy OR biofuel) AND ("renewable energy" OR "sustainable energy") AND (benefits OR potential). This adjustment led to the exclusion of 4,477 articles that did not align with the review's core focus, resulting in 534 relevant records.

To ensure the inclusion of the most recent and contextually relevant studies, a publication year filter was applied, limiting the dataset to articles published between 2023 and 2025. This step excluded 385 articles outside the temporal scope, reducing the pool to 149 publications. Further screening was conducted to ensure accessibility, retaining only articles classified as Open Access or available through Open Archive. As a result, 106 articles were removed, producing a final dataset of 43 peer-reviewed articles selected for full-text analysis. All sources were curated and managed using Mendeley Desktop to ensure accurate referencing, eliminate duplication, and maintain consistent citation formatting throughout the review process.

Importantly, this study relies exclusively on secondary data sourced from existing literature and does not involve any primary data collection, such as field observations or focus group discussions (FGDs). By adhering strictly to SLR protocols and drawing on peer-reviewed sources, this article provides a reliable, unbiased academic foundation for understanding the benefits of oil palm biomass across industrial and environmental contexts.

Results

This Systematic Literature Review (SLR) analyzed 43 peer-reviewed journal articles published between 2023 and 2025, focusing on the utilization and valorization of oil palm biomass across energy, environmental, and industrial domains. Using PRISMA methodology, the extracted data were thematically categorized into six dominant research areas: (1) Hybrid Energy Harvesting Techniques, (2) Environmental Energy Sources, (3) System Architecture and Bioenergy Optimization, (4) Carbon Footprint Reduction and Emissions Control, (5) Techno-Economic Feasibility and Market Potential, and (6) Waste Valorization and Circular Economy Applications.

Analysis of the thematic distribution reveals the following proportions: Hybrid Energy Harvesting Techniques were discussed in 23.3% of the studies, followed by System Architecture and Bioenergy Optimization in 18.6%, Environmental Energy Sources and Techno-Economic Feasibility (both at 16.3%), Carbon Footprint Reduction and Emissions Control at 13.9%, and Waste Valorization and Circular Economy Applications at 11.6%. Notably, several articles addressed multiple thematic areas, underscoring the interrelated nature of oil palm biomass research, particularly where technical innovation intersects with environmental performance and economic viability.

The predominance of hybrid energy systems reflects the growing urgency to ensure stable, decentralized energy access in remote regions, especially in Southeast Asia. This trend highlights a shift toward energy diversification strategies that blend oil palm biomass with solar, wind, and biogas technologies to enhance energy security and reduce intermittency. System optimization also emerged as a strong theme, pointing to the importance of improving efficiency, cost-effectiveness, and system design, especially in industrial and rural electrification contexts.

Environmental energy themes and techno-economic analyses received balanced attention, suggesting that the research community is simultaneously concerned with environmental benefits (such as emissions reduction) and market feasibility. In contrast, waste valorization received the least attention, likely due to its interdisciplinary complexity and the relatively recent expansion of oil palm biomass applications into material science, agriculture, and bio-industrial sectors.

These thematic trends suggest a scholarly focus primarily driven by the energy and economic value of oil palm biomass, while areas such as material valorization and circular economy integration are emerging as new frontiers. This signals important implications: future research must not only continue optimizing bioenergy systems but also expand toward full-spectrum utilization of biomass to support a broader transition toward resource circularity, emissions reduction, and sustainable industrial transformation.

The following sections explore each of the six themes in greater detail, supported by empirical evidence from the reviewed literature.

Hybrid Energy Harvesting Techniques

Oil palm biomass has been increasingly explored in conjunction with hybrid energy systems, particularly in Southeast Asia, where biomass is integrated with solar, wind, or biogas systems to ensure consistent energy generation. In rural Malaysia, studies demonstrated that integrating oil palm empty fruit bunch (EFB) biomass with photovoltaic (PV) systems enhanced power stability by 17.3% over solar-only systems, while reducing energy intermittency during cloudy seasons by up to 24% [21]. A hybrid system implemented in South Kalimantan that combined mesocarp fiber combustion with solar PV produced a total energy output of 5.1 MW and provided an uninterrupted power supply to 11,000 households over a two-year pilot program [22].

Further research in Sarawak reported that coupling anaerobic digestion of palm oil mill effluent (POME) with micro-hydro turbines increased energy security in flood-prone areas, generating 3.4 MWh daily with a 91.2% system reliability factor [23]. Moreover, hybrid systems that leverage both thermal and biological conversion of biomass materials were found to improve energy conversion efficiency by up to 28.5% compared to standalone combustion systems [24]. The integration of gasification with battery storage in oil palm estate microgrids demonstrated a 36% improvement in load-balancing capabilities, critical for rural electrification [25].

Environmental Energy Sources

Oil palm biomass presents a renewable, locally available, and environmentally beneficial energy source with significant untapped potential. The calorific value of palm kernel shell ranges from 18.7 to 20.1 MJ/kg, comparable to low-grade coal but with a 46% lower sulfur content, thereby minimizing acid rain risk [26]. Utilization of EFB for pellet fuel production has shown emission reductions of 53% compared to diesel generators in off-grid settings, with lifecycle CO_2 savings of 1.92 kg CO_2/kWh [27].

Indonesia's Ministry of Energy and Mineral Resources projects that palm biomass could generate up to 135 million GJ/year by 2035, offsetting 10.4% of total national energy demand and contributing to 18.1 million tons of avoided CO_2 annually [28]. Methane recovery from POME can reach concentrations of 63–67%, yielding 30–34 m^3 CH_4/tonne of effluent, equivalent to a heating value of 24.7 MJ/m^3 [29]. Additionally, co-firing palm biomass with rice husk in hybrid boilers achieved 89.3% combustion efficiency while cutting NO_x emissions by 42% [30].

System Architecture and Bioenergy Optimization

Advanced system architecture is essential for optimizing energy recovery from oil palm biomass. Research has shown that co-firing palm biomass in fluidized bed reactors at 750°C improves combustion efficiency by 21.4% and reduces unburned carbon residues by 35%, with ash content below 3.7% [31]. Integration of torrefaction pretreatment into biomass-to-energy pipelines reduces moisture content by 38%, increases grindability by 46%, and extends storage stability to up to 8 months [32].

A techno-structural model developed for a biomass gasification plant in Perak projected a levelized cost of electricity (LCOE) of $0.078/kWh when using a blend of mesocarp fiber and shell, undercutting diesel-based electricity production by 34% [33]. In Thailand, AI-enabled optimization algorithms improved biomass boiler efficiency by 15.2%, reducing energy losses from thermal fluctuations [34]. Additionally, integrating combined heat and power (CHP) systems in palm oil mills has achieved a thermal efficiency of 72.3%, significantly improving energy self-sufficiency [35].

Carbon Footprint Reduction and Emissions Control

The deployment of oil palm biomass in energy systems has demonstrated tangible carbon mitigation benefits. Comparative lifecycle assessment (LCA) studies indicate that biomass-based electricity generation reduces CO_2-equivalent emissions by 74–81% relative to coal-fired power [36]. For instance, a biomass cogeneration plant operating in Johor reported annual GHG savings of approximately 92,000 metric tons of CO_2-eq, equivalent to removing 19,400 cars from the road [37].

In field trials across Sumatra, applying EFB compost as an organic fertilizer reduced synthetic nitrogen inputs by 56%, thereby indirectly reducing nitrous oxide emissions by 1.2 t/ha/year [38]. EFB biochar applied in degraded peatland soils captured 15.2 t CO_2/ha/year and increased soil carbon content by 32% over three planting cycles [39]. Methane recovery through POME biogas digesters at 27 industrial-scale mills avoided 1.9 million tons of CO_2-eq emissions annually across Indonesia [40].

Techno-Economic Feasibility and Market Potential

Numerous studies have evaluated the commercial viability of oil palm biomass in both domestic and export markets. The global biomass pellet market is forecast to reach USD 18.3 billion by 2030, with palm-based biomass accounting for 12–15% of ASEAN production, equivalent to 2.4–2.9 million tonnes per year [41]. In Malaysia, feed-in-tariff (FiT) schemes for biomass electricity have accelerated deployment, with a tariff rate of RM 0.312/kWh contributing to 11.2% growth in renewable energy investments between 2022 and 2024 [42].

Capital expenditure (CAPEX) for small-scale biomass gasifiers ranges from USD 1,500–2,100 per kW of installed capacity, with a projected internal rate of return (IRR) of 12.5%-18.9%, depending on feedstock price stability and policy incentives [43]. Export data indicates that palm biomass briquettes from Indonesia reached 187,000 tonnes in 2023, a 29% increase from the previous year, driven by demand from South Korea and Japan for co-firing in biomass power plants [44].

In Sabah, a techno-economic assessment of a 10 MW biomass power plant using palm shell feedstock estimated a payback period of 5.7 years under current FiT policies [45]. Moreover, carbon credit valuation from avoided methane emissions adds an additional USD 14.5/ton CO_2-eq to project revenues in CDM-certified projects [46].

Waste Valorization and Circular Economy Applications

Oil palm biomass valorization extends beyond energy into materials science, agriculture, and bioproducts. For instance, EFB-derived cellulose nanofibers have been used to produce biodegradable packaging with tensile strengths up to 98 MPa, rivaling those of petroleum-based plastics [47,48]. Research at Universiti Putra Malaysia demonstrated that oil palm mesocarp fiber could be converted into fiberboard panels with 0.62 g/cm^3 density and 92% dimensional stability [49,50].

Studies on biochar derived from mesocarp fiber show that it enhances soil pH by 0.7–1.2 units and increases maize yield by 27.4% in acidic tropical soils [51]. Additionally, lignin extracted from palm biomass has been used as a precursor in bio-based adhesives and resin composites, improving bonding strength in wood panels by 41% compared to synthetic resins [52,53]. In cement manufacturing, palm biomass ash has replaced up to 25% of clinker content, lowering CO_2 emissions from cement production by 18% and reducing energy input per ton by 11.7% [54,55].

Bioplastics derived from palm oil waste polymers have achieved biodegradation rates of 61–68% over 90 days in composting environments, with mechanical properties suitable for disposable utensils and agricultural films [56,57]. Industrial trials in Selangor produced biodegradable mulch films from palm starch-polyester blends at a cost of USD 2.16/kg, competitive with petrochemical-based alternatives [58,59].

Oil palm frond pulp has also shown promise as a feedstock for paper production, yielding up to 56.8% pulp yield with ISO brightness values of 62.3% after elemental chlorine-free bleaching [60,61]. Residues such as palm press fiber and shell have been used as raw materials for activated carbon production, achieving surface areas of 960 m^2/g and demonstrating effectiveness for wastewater adsorption applications [62,63]. Such cross-sector valorization enhances economic circularity and reduces pressure on landfills.

This SLR, it demonstrates that oil palm biomass offers a versatile, high-impact pathway toward sustainable development. Across energy, agriculture, environmental, and industrial domains, the 43 reviewed studies consistently highlight the environmental efficacy, economic viability, and technical feasibility of oil palm biomass utilization. While challenges remain in standardization, policy harmonization, and cross-sector integration, the growing body of literature underscores a paradigm shift: from waste to value, from residue to resource. This transformation positions oil palm biomass not only as an energy asset but also as a foundation for circular-economy innovation.

Discussion

The systematic analysis of 43 peer-reviewed articles has led to a detailed understanding of the multifaceted benefits of oil palm biomass, as well as the barriers and enablers that influence its effective valorization. This discussion is organized to directly address the two central research questions: (1) the primary technological, environmental, and economic benefits of oil palm biomass, and (2) the enablers and constraints affecting its practical utilization. Each thematic component is examined through the lens of recent literature published between 2023 and 2025.

Technological, Environmental, and Economic Benefits of Oil Palm Biomass

Technological Advancements and Conversion Efficiency

Recent advancements in thermochemical and biochemical conversion technologies have significantly improved the efficiency and viability of oil palm biomass utilization. Technologies such as gasification, pyrolysis, and hydrothermal liquefaction now enable the conversion of empty fruit bunches (EFB), palm kernel shells (PKS), and mesocarp fibers into bio-oil, syngas, and biochar, with yields exceeding 65% under optimized conditions [64]. Moreover, enzyme-catalyzed fermentation of oil palm trunk sap and fibers has yielded bioethanol at up to 0.45 g/g, approaching industrial standards [65]. Hybrid systems that integrate anaerobic digestion with thermochemical processes have demonstrated energy recovery efficiencies above 75%, highlighting the promising technological synergies achievable in integrated biomass systems [66].

Environmental Contributions and Carbon Mitigation

The environmental value of oil palm biomass is closely tied to its capacity to offset carbon emissions and reduce waste. Replacing coal with PKS in co-firing scenarios can reduce CO_2 emissions by up to 62% per MWh of electricity produced, according to life-cycle assessments [67]. Biochar derived from pyrolyzed biomass not only sequesters carbon but also improves soil fertility, water retention, and microbial activity, making it a dual-purpose product with climate-smart applications [68].

Furthermore, using mill residues and plantation waste reduces open burning, which remains a significant contributor to air pollution and PM2.5-related health burdens in Southeast Asia [69].

In palm oil-producing countries, biomass valorization is increasingly positioned as a strategy to reduce methane emissions from untreated palm oil mill effluent (POME). Anaerobic digestion systems can capture and utilize over 70% of methane that would otherwise escape into the atmosphere, transforming POME into biogas and biofertilizers [70].

Economic Potential and Circular Value Chains

Economically, the valorization of oil palm biomass contributes to the establishment of circular bio economies that can generate diverse revenue streams for stakeholders across the value chain. In Indonesia and Malaysia, revenue from PKS exports alone reached USD 1.4 billion in 2024, driven by demand from Japan and South Korea's biomass power sectors [71]. At the microeconomic level, smallholders supplying biomass to local biorefineries experience an average annual income increase of 18% compared to those reliant solely on crude palm oil production [72].

Cost-benefit analyses across multiple studies have shown that the internal rate of return (IRR) for biomass gasification plants using oil palm waste ranges from 16% to 22%, surpassing those of many conventional renewable energy investments [73]. Furthermore, the development of decentralized biomass energy systems has enhanced rural electrification and reduced dependency on fossil fuels, promoting energy sovereignty in remote plantation communities [74].

Enablers and Constraints in the Valorization of Oil Palm Biomass

Institutional and Policy Frameworks

The successful deployment of oil palm biomass technologies depends on coherent institutional frameworks and favorable policy environments. In recent years, national policies such as Indonesia's Renewable Energy Master Plan and Malaysia's Biomass Industry Action Plan have outlined strategic objectives to scale up biomass valorization [75]. Feed-in tariffs (FiTs), tax exemptions, and green bond incentives have enabled capital mobilization for biomass-to-energy projects in rural districts [76].

Nevertheless, policy fragmentation and inconsistent enforcement remain significant constraints. Regulatory overlaps between forestry, agriculture, and energy ministries can delay project approvals, while the absence of standardized sustainability certification for biomass products creates market uncertainty [77]. The lack of binding carbon-pricing mechanisms also limits the financial attractiveness of biomass relative to conventional fossil fuel options in some regions.

Technical Infrastructure and Supply Chain Logistics

Infrastructure gaps, particularly in rural plantation regions, continue to hinder the logistics and scalability of biomass collection and transport. High moisture content and dispersed biomass sources necessitate localized preprocessing hubs to improve efficiency and reduce transportation costs, which can account for up to 40% of total operational expenses in current systems [78]. Additionally, storage degradation and seasonal variability of feedstock quality introduce further uncertainties in biomass supply chains [79].

Enabling factors include the emergence of digital traceability platforms and AI-assisted predictive maintenance tools for biomass conversion systems. These technologies enhance operational reliability and supply chain transparency, especially in small and medium-scale processing units [80].

Knowledge, Awareness, and Stakeholder Participation

Community engagement and stakeholder awareness are critical enablers in the success of biomass valorization projects. Evidence from participatory projects in Riau and Sabah shows that inclusive biomass programs those involving local cooperatives and NGOs achieve 30–50% higher project adoption and long-term sustainability [81]. However, a prevailing knowledge gap regarding the commercial potential of biomass products persists among smallholders and local governments, limiting widespread adoption.

Capacity-building initiatives, extension services, and training in biomass handling and quality control have been identified as crucial mechanisms to bridge these gaps. Knowledge-sharing partnerships between academia, industry, and government are also facilitating the dissemination of best practices, especially in countries where oil palm is a major economic sector.

The findings of this SLR highlight that oil palm biomass represents a viable, multi-benefit resource capable of supporting sustainable development goals (SDGs) through technological innovation, environmental restoration, and socio-economic advancement. However, its full potential remains underexploited due to structural, logistical, and informational barriers. To address these challenges, future research should focus on quantifying the long-term ecological impacts of large-scale biomass utilization, optimizing hybrid conversion pathways, and developing harmonized policy frameworks across oil palm-producing nations.

There is also a need to more comprehensively explore the social dimensions of biomass valorization, particularly gender equity, labor dynamics, and benefit-sharing mechanisms. In addition, techno-economic modeling across varying market and policy scenarios will be essential to inform strategic planning and investment decisions.

The valorization of oil palm biomass presents substantial technological, environmental, and economic advantages. However, unlocking these benefits on a wide scale will require integrated policy support, infrastructure investment, and strengthened community participation. These insights aim to inform stakeholders, policymakers, and researchers in shaping more inclusive and effective strategies for biomass development in the oil palm sector.

Conclusion

This systematic literature review synthesizes evidence from 43 high-quality peer-reviewed articles to provide a comprehensive understanding of the multifaceted benefits and real-world applicability of oil palm biomass. Across technological dimensions, oil palm biomass has emerged as a viable renewable energy source, supporting advancements in thermal conversion technologies such as pyrolysis, gasification, and co-firing, as well as integration into hybrid renewable energy systems. These technologies have demonstrated high energy efficiency and reliability, particularly in decentralized energy applications. Additionally, innovations in biorefinery and biochar production underscore the versatility of oil palm biomass as a valuable industrial feedstock.

Environmentally, the use of oil palm biomass significantly reduces greenhouse gas emissions, with several studies reporting up to 65% lower CO_2 emissions than fossil fuel baselines. Biomass valorization also mitigates environmental pollution from palm oil mill residues, enhances soil quality through biochar application, and supports a circular bioeconomy by transforming agricultural waste into valuable resources. Economically, valorizing oil palm biomass offers strong financial returns, with reported internal rates of return (IRR) exceeding 18% in several commercial-scale implementations. It also provides substantial socioeconomic benefits by generating rural employment and fostering local industrial development, particularly in biomass pellet production and bioenergy supply chains.

The review further identifies key enabling conditions for successful biomass valorization, including supportive renewable energy policies, technological accessibility, academic-industry partnerships, and incentives for circular economy practices. However, significant barriers persist. These include high upfront capital costs, logistical challenges in biomass collection and transport, limited technical literacy among smallholders, and regulatory fragmentation across sectors. Additionally, misconceptions equating biomass use with deforestation continue a constrain public acceptance and investment.

Overall, oil palm biomass is a strategically underutilized resource with significant potential to support energy diversification, rural development, and climate-mitigation goals. The body of evidence underscores the need for targeted interventions that address implementation barriers while leveraging proven enablers. Future research should focus on site-specific life-cycle assessments, decentralized bioindustrial systems, and policy harmonization strategies to accelerate sustainable biomass deployment in palm oil-producing regions.

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