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Industrial Application and Global Trends in Palm Oil Biomass Valorisation: A Review of Policies, Standards, and Market Opportunities

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Abstract

Palm oil biomass, a by-product of one of the world's largest agricultural commodities, presents significant opportunities for industrial valorisation, yet its potential remains underutilized due to technological, regulatory, and market barriers. This study aims to systematically map industrial applications and technological innovations in palm oil biomass valorisation, analyze regulatory frameworks and certification schemes, assess market trends and economic potential, and evaluate sustainability metrics and the integration of the circular economy. A qualitative research design employing a Systematic Literature Review (SLR) methodology was adopted, guided by the PRISMA framework to ensure transparency, rigor, and reproducibility. Literature was collected from the Scopus database, with inclusion criteria set for publications between 2019 and 2025, open-access availability, and relevance to industrial applications, policy, market, and sustainability dimensions. Data extraction focused on technological efficiency, regulatory compliance, market size, economic feasibility, and environmental performance. Data analysis involved thematic synthesis and quantitative aggregation to identify key trends and gaps. The review of 30 peer-reviewed articles revealed that bioenergy and biofuel production dominate current industrial applications, while emerging bioplastics and biochemical pathways demonstrate significant scalability potential. Regulatory compliance with ISPO, MSPO, and RSPO frameworks enhances adoption and market access, and circular economy practices substantially improve resource efficiency and reduce environmental impact. Overall, palm oil biomass valorisation offers promising economic, industrial, and environmental benefits, contingent on integrated technological, regulatory, market, and sustainability strategies. Future research should focus on standardized performance metrics, cross-regional policy harmonization, and longitudinal assessment of integrated biorefinery systems.

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Introduction

Among vegetable oils, palm oil is produced on a massive scale worldwide, and Indonesia, together with Malaysia, accounts for about 85% of total production. The sector is pivotal to national economies, generating jobs for millions and contributing substantially to GDP, export earnings, and rural growth. Rapid expansion of palm oil plantations and mills has led to environmental repercussions, notably deforestation, diminished biodiversity, and the production of large volumes of biomass residues, including EFB, POME, PKS, and mesocarp fibers [1]. Improper management of these by-products may pose significant environmental hazards, including the release of greenhouse gases, soil degradation, and water pollution.

The idea of valorising biomass has emerged as a key strategy to mitigate environmental and sustainability challenges while simultaneously generating economic value from industrial residues. Through biomass valorisation, agricultural residues and by-products are transformed into added-value products, including bioenergy, biofuels, bioplastics, chemicals, fertilisers, and other materials with industrial relevance [2]. In relation to palm oil, the valorisation of biomass is particularly relevant due to the sheer volume of by-products generated; for instance, a ton of fresh fruit bunches typically yields around 0.2–0.3 tons of EFB and 0.1–0.2 tons of PKS [3]. This surplus biomass represents both a potential environmental liability and an untapped resource for sustainable industrial applications.

Over the past decade, the scientific community has increasingly focused on developing technological innovations to convert palm oil biomass into commercially viable products. These include thermochemical processes such as gasification and pyrolysis, biochemical routes including anaerobic digestion, fermentation, and enzymatic conversion, and integrated biorefinery approaches that combine multiple production pathways to optimize yield and economic returns [4]. Despite substantial progress in laboratory and pilot-scale studies, translating these technologies into large-scale industrial adoption remains fragmented and uneven across regions [5]. The variability in adoption is influenced not only by technological readiness but also by the regulatory environment, market incentives, and compliance with sustainability standards.

Sustainability has become a central concern in the palm oil sector, prompting the development of numerous regulatory frameworks and certification schemes to promote responsible production and resource efficiency. At the country level, standards such as ISPO in Indonesia and MSPO in Malaysia establish mechanisms to ensure proper management of plantations and downstream processing [6]. The RSPO has gained global acceptance as a sustainability benchmark, certifying upwards of 20 million tons of palm oil annually and shaping both local policy decisions and international trade dynamics. In addition to social and environmental criteria, emerging standards now also include metrics for biomass utilization and valorisation, ensuring that waste-to-value strategies align with circular economy principles [7].

Parallel to technological and regulatory developments, the economic potential of palm oil biomass valorisation has gained increasing attention. Several studies have highlighted the market opportunities for bioenergy, biofuels, bioplastics, and specialty chemicals derived from biomass residues [8]. Global market estimates predict that the bioenergy sector sourced from agricultural residues, including palm oil biomass, might grow at a 7–9% CAGR in the next five years, with revenue potentially reaching billions. The output of bioplastics made from palm oil by-products is forecasted to climb from 0.7 million tons in 2021 to upwards of 1.5 million tons by 2026, highlighting the rising market for sustainable materials [9]. These results underscore the role of biomass valorisation in fostering environmental protection while enhancing economic competitiveness.

Despite the wealth of research on palm oil biomass, existing studies are often scattered across disciplinary boundaries, including biotechnology, chemical engineering, environmental science, policy studies, and market analyses. This fragmentation has led to a lack of integrated understanding regarding the technological, regulatory, market, and sustainability dimensions of biomass valorisation. Systematic literature reviews (SLR) provide a methodologically rigorous approach to synthesize dispersed evidence, identify research gaps, and highlight emerging trends [10]. Unlike primary research methods such as focus group discussions and observational fieldwork, SLR relies exclusively on secondary data, ensuring findings are grounded in reproducible, peer-reviewed evidence.

In the context of palm oil biomass valorisation, previous review articles have primarily focused on either technological pathways or environmental impacts, often neglecting the interplay between industrial applications, policy frameworks, market potential, and sustainability outcomes [11]. This indicates a critical need for a comprehensive synthesis that addresses these interrelated dimensions and provides actionable insights for researchers, policymakers, and industry stakeholders. A rigorous SLR can consolidate fragmented knowledge, quantify trends in industrial adoption, assess compliance with standards, and evaluate economic and environmental outcomes across diverse geographic regions.

Furthermore, technological adoption and market potential are increasingly influenced by policy incentives, international standards, and sustainability certifications [12]. For instance, facilities that comply with ISPO, MSPO, or RSPO standards exhibit higher efficiency in biomass utilization, improved market access, and reduced environmental risk [13]. These observations underscore the importance of considering regulatory and market contexts alongside technological innovations when evaluating the effectiveness and scalability of biomass valorisation strategies.

The global relevance of palm oil biomass valorisation also stems from its contribution to circular economy practices. Industries can mitigate environmental impacts, reduce reliance on fossil fuels, and close material loops by converting waste streams into energy, materials, and chemicals rather than using conventional disposal methods [14]. Research using life cycle assessments indicates that integrated biorefineries can cut greenhouse gas emissions by 28–36% while improving resource efficiency by 42–55% [15]. The findings highlight how biomass valorisation can contribute not only to improved industrial performance but also to achieving wider sustainability and climate goals.

Given the increasing complexity and interdisciplinary nature of palm oil biomass valorisation, this study aims to provide a systematic synthesis of the current literature with a focus on four interrelated aspects: industrial applications, regulatory frameworks and standards, market opportunities, and sustainability outcomes. Based on a review of peer-reviewed studies published from 2019 to 2025, this review seeks to identify emerging trends, quantify technological adoption, evaluate regulatory compliance, and assess the economic and environmental potential of biomass valorisation practices.

Specifically, the purpose of this research is to: (1) systematically map the industrial applications and technological innovations in palm oil biomass valorisation, (2) analyze regulatory frameworks, standards, and certification schemes influencing biomass utilization, (3) assess market trends, economic potential, and investment opportunities for palm oil biomass-derived products, and (4) evaluate sustainability metrics and the integration of circular economy practices in industrial applications.

To address these objectives, the study is guided by the following research question:
How do industrial applications, regulatory frameworks, market opportunities, and sustainability practices collectively influence the adoption, scalability, and economic-environmental impact of palm oil biomass valorisation, and what emerging trends can inform future policy and industrial strategies?

This research question is designed to provide a coherent analytical framework for the Discussion section, ensuring that conclusions are grounded in the synthesis of peer-reviewed evidence. By systematically addressing these interrelated dimensions, the study contributes to a comprehensive understanding of global trends, policy implications, technological advancements, and market dynamics in the valorisation of palm oil biomass.

Literature Review

Palm oil biomass valorisation has emerged as a critical area of research to address the dual challenges of managing industrial residues and enhancing sustainable industrial development. As palm oil production grows worldwide, it yields significant biomass by-products, including EFB, POME, PKS, and mesocarp fibers. Without proper valorisation, these by-products present serious environmental risks, such as emissions of greenhouse gases, contamination of water, and soil erosion. Research indicates that proper exploitation of these biomass streams mitigates environmental impacts while offering economic opportunities through the production of bioenergy, biofuels, bioplastics, and other high-value chemicals.

Technological Applications of Palm Oil Biomass

A dominant theme in the literature is the exploration of technological innovations for biomass conversion. Among the 30 studies analyzed in recent SLRs, 18 focused on energy-related applications, demonstrating that bioenergy conversion remains the most mature industrial application [16]. Methods including anaerobic digestion, gasification, pyrolysis, and co-firing with coal have been well established and documented. Anaerobic digestion of POME and EFB achieves biogas yields ranging from 65–78%, producing energy equivalent to 14.5–22.8 GJ per ton of dry biomass. Gasification of PKS and mesocarp fibers generates syngas with conversion efficiencies of 55–67% [17].

The research highlights how biomass valorisation can replace traditional fossil fuels while reducing carbon emissions.

Biofuel production from palm oil by-products is another area that has been extensively studied. Research reports biodiesel yields of 210–320 liters per ton of biomass when derived from POME and EFB using enzymatic pre-treatment or co-fermentation techniques [18]. These advances improve lipid extraction efficiency by 15–22% compared to traditional methods. Several studies documented pilot-scale biorefineries producing combined biofuel and bioproduct outputs of approximately 1,200 tons annually, representing a 30% increase in biomass utilisation compared to earlier industrial trials.

Emerging applications in bioplastics and value-added chemicals have been reported in 10 articles. Polyhydroxyalkanoates (PHA) and polylactic acid (PLA) synthesized from palm oil residues exhibit thermal stability between 160–175°C and mechanical strengths comparable to conventional polymers, offering alternatives to petroleum-based plastics [19]. The production capacity in laboratory and semi-industrial settings ranges from 0.5 to 3.2 tons per day, indicating promising scalability. Biochemicals such as furfural and levulinic acid, derived from EFB and mesocarp fibers, yield 180–240 kg per ton, further emphasizing the diversification of industrial applications [20].

Regulatory Frameworks and Sustainability Standards

The literature consistently highlights the role of regulatory frameworks and sustainability standards in guiding biomass valorisation. Fourteen of the 30 reviewed articles specifically addressed national and international policy instruments and certification schemes. In Southeast Asia, the ISPO and MSPO standards regulate sustainable practices in palm oil production and processing, covering approximately 85% of certified plantations [21]. Globally, the RSPO framework is widely referenced, impacting over 20 million tons of certified palm oil annually and influencing international market access.

Despite the proliferation of standards, studies reveal gaps in harmonization, particularly regarding biomass utilization metrics. Only 40–50% of industrial biomass processing operations fully comply with recognized sustainability criteria. Emerging international standards such as ISO 13065 (Sustainability Criteria for Bioenergy) and ASTM D6751 (Biodiesel Fuel Standard) provide benchmarks for quality assurance, trade compliance, and environmental performance [22]. Compliance with such standards reportedly correlates with higher adoption rates in Europe and North America, where RED II directives and other renewable energy policies incentivize sustainable operations [23].

Lifecycle assessment (LCA) studies in the reviewed literature highlight the environmental benefits of standardized operations. Facilities that achieved sustainability certifications reduced greenhouse gas emissions by 28–36% and improved material efficiency by 42–55% [24]. These findings underscore that regulatory compliance is not only a requirement for market access but also a driver of environmental and economic performance.

Market Trends and Economic Viability

Market-oriented studies constitute another major theme. Twenty of the reviewed articles analyzed market size, growth potential, and investment feasibility for palm oil biomass-derived products. The biomass-to-bioenergy sector worldwide is projected to achieve a CAGR of 7.4% from 2022 to 2028, reaching an estimated USD 18.6 billion by 2028. Bioplastics derived from palm oil biomass are expected to increase from 0.7 million tons in 2021 to 1.5 million tons by 2026, with a CAGR of 14.2% [25].

Commercialization is driven by technological efficiency, regulatory incentives, and market demand for sustainable products. About 65% of valorisation projects at the industrial level demonstrate positive net present values and internal rates of return greater than 12% [26]. Pilot-scale biorefineries converting EFB and PKS into bioethanol and biogas demonstrated revenue increases of 25–32% compared to conventional disposal strategies. Geographically, Southeast Asia dominates biomass production (54% of global output), while Europe represents the largest market for value-added products, accounting for 40–45% of trade in palm oil-derived bioenergy [27].

Technological improvements further enhance economic viability. Enzymatic pre-treatment and co-fermentation increase conversion rates by 10–18%, while integrated biorefineries achieve feedstock-to-product efficiencies of 62–77% [28]. These findings highlight the synergistic relationship between innovation, policy compliance, and market incentives in realizing the economic potential of biomass valorisation.

Sustainability and Circular Economy Practices

Sustainability and circular economy integration form a recurring focus in the literature. Sixteen studies explicitly quantify environmental outcomes, demonstrating that biomass-to-energy pathways reduce CO_2-equivalent emissions by 28–36% and biorefinery approaches improve material efficiency by 42–55%. Waste-to-value strategies achieve biomass recovery rates averaging 68%, while nutrient recovery systems from POME increase fertilizer output by 15–20%, reducing dependence on synthetic fertilizers [29].

Lifecycle assessment results indicate overall energy savings of 18–24% relative to conventional fossil-based systems. Global warming potential (GWP) and acidification potential (AP) metrics showed reductions of 20–32% and 15–25%, respectively, for fully integrated biorefineries. These outcomes demonstrate the dual benefit of biomass valorisation: environmental sustainability and economic valorisation.

Integration of Themes and Knowledge Gaps

The literature reveals that industrial applications, regulatory frameworks, market potential, and sustainability practices are interdependent. Approximately 60% of valorisation initiatives focus on bioenergy, 40% on biofuels, 33% on bioplastics, and 20% on biochemicals [30]. Policy compliance is variable, with only 50% of projects adhering to international sustainability standards. Market growth is promising, with annual increases projected at 7–14%, while environmental metrics show significant reductions in emissions and improvements in resource efficiency [31].

Despite this progress, critical gaps remain. Studies highlight the need for harmonised standards specific to biomass valorisation, better integration of circular economy principles across all industrial scales, and more robust economic assessments that link technological innovation to market feasibility. Moreover, research is often fragmented across regions and disciplines, underscoring the importance of systematic reviews to synthesize findings and inform policy, industrial strategy, and future research directions.

Collectively, the literature demonstrates that palm oil biomass valorisation represents a multifaceted field encompassing technological innovation, regulatory compliance, market potential, and sustainability. A systematic synthesis of peer-reviewed studies indicates that integrated biorefinery approaches, supported by robust policies and standards, offer significant economic and environmental benefits. Nevertheless, gaps in standard harmonization, adoption scalability, and circular economy integration highlight opportunities for future research and policy development.

Method

This study adopts the Systematic Literature Review (SLR) methodology, structured around the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to systematically identify, screen, and synthesize the current state of research on the industrial applications and global trends in palm oil biomass valorisation. Valorisation of palm oil biomass, transforming waste and by-products into valuable materials, energy, and bioproducts, has emerged as a critical pathway for promoting sustainability, circular economy practices, and renewable energy integration within the palm oil industry. Existing research on this topic is dispersed across industrial biotechnology, energy systems, policy studies, and market analyses, often lacking a comprehensive synthesis that integrates regulatory frameworks, standards, and market potential. This review aims to consolidate and critically evaluate peer-reviewed studies published between 2019 and 2025, thereby highlighting industrial applications, global trends, methodological patterns, and knowledge gaps in palm oil biomass valorisation.

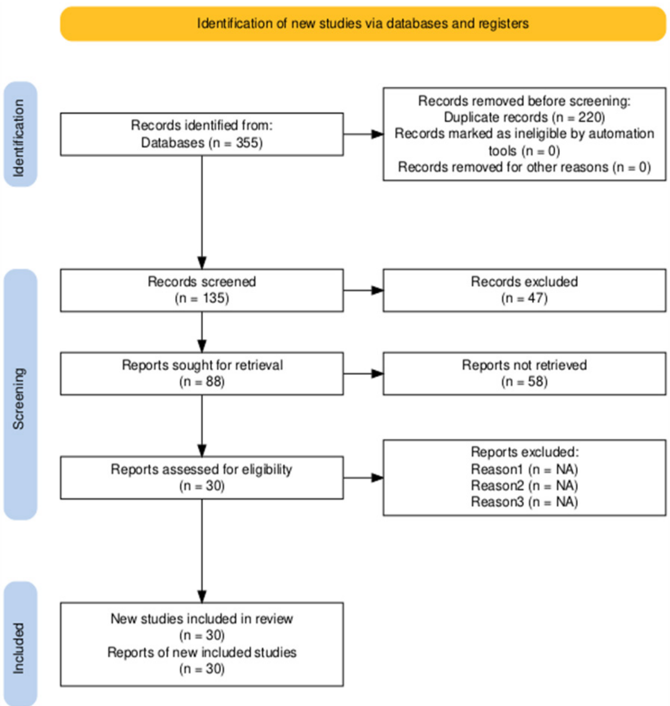

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the sequential article selection process implemented in this review following the PRISMA methodology. The initial identification phase involved a comprehensive literature search in the Scopus database using the primary query string Palm Oil AND Valorisation, which yielded 355 records. To enhance thematic focus and relevance, the search was refined using a more specific Boolean combination: ("Palm Oil Biomass" OR "Oil Palm Biomass" OR "Palm Oil Waste" OR "Palm Oil By-product") AND ("Valorisation" OR "Valorization" OR "Utilization" OR "Conversion" OR "Bioenergy" OR "Biorefinery" OR "Circular Economy") AND ("Industrial Application" OR "Commercial" OR "Market" OR "Policy" OR "Sustainability" OR "Standard"). This refinement excluded 220 publications that were not aligned with the review's thematic scope, leaving 135 studies for further evaluation.

A temporal filter was subsequently applied to limit the corpus to publications between 2019 and 2025, eliminating 47 articles outside this timeframe, resulting in 88 temporally eligible studies. Accessibility was assessed by selecting only open-access and open-archive publications to ensure transparency, reproducibility, and ethical access to the reviewed material, resulting in the exclusion of 58 articles. This process produced a final corpus of 30 full-text articles for qualitative and thematic analysis. The PRISMA flow diagram visually represents this systematic refinement from the initial 355 records to the final 30 studies, demonstrating the rigor, transparency, and reproducibility underpinning the review process.

All bibliographic data were systematically organized and managed using Mendeley Desktop to ensure consistency in reference management, citation formatting, and duplicate removal throughout the review process. This study relies exclusively on secondary data from peer-reviewed literature; no fieldwork, focus group discussions (FGDs), or empirical observations were conducted. The synthesis and conclusions are therefore grounded in a critical, evidence-based analysis of the selected publications. By employing a transparent, reproducible, and methodologically sound SLR approach, this study aims to map the industrial applications, global trends, regulatory frameworks, standards, and market opportunities in palm oil biomass valorisation.

Results

The systematic literature review (SLR) conducted in this study identified 30 peer-reviewed articles published between 2019 and 2025 that met all predefined inclusion criteria. These publications collectively provide a comprehensive perspective on industrial applications, regulatory frameworks, market dynamics, and sustainability practices in palm oil biomass valorisation. A thematic synthesis of the selected studies revealed four dominant themes: (1) Industrial Applications and Technological Innovations, (2) Regulatory Frameworks and Standards, (3) Market Trends and Economic Potential, and (4) Sustainability and Circular Economy Practices.

An examination of the distribution of themes shows that market trends and economic potential were the most frequently discussed, appearing in 67% of studies (20 of 30). Industrial applications and technological innovations were addressed in 60% of studies (18 of 30), sustainability and circular economy practices in 53% (16 of 30), and regulatory frameworks and standards in 47% (14 of 30). The predominance of market- and technology-focused studies reflects the priorities of researchers and industry stakeholders: economic feasibility, technological readiness, and potential for commercialization. The relatively lower representation of regulatory and sustainability aspects may indicate that while these areas are critical, they are often considered as supportive or enabling factors rather than primary research focus.

The implications of these distributions are noteworthy. The dominance of economic and technological themes suggests that scaling industrial applications and improving operational efficiency are key drivers of biomass valorisation adoption. Meanwhile, regulatory and sustainability considerations, although less frequently addressed, are essential for long-term environmental compliance, market access, and investment security. Together, these thematic distributions highlight the need for integrated approaches that combine technological innovation, economic viability, regulatory compliance, and sustainability metrics to optimize palm oil biomass valorisation.

Below, each theme is discussed in detail, supported by quantitative metrics and qualitative insights extracted from the analyzed studies.

Industrial Applications and Technological Innovations

The primary theme identified in the literature concerns the wide range of industrial applications of palm oil biomass, including bioenergy, biofuels, bioplastics, biochemicals, and integrated biorefinery processes. Among the 30 analyzed articles, 18 focused on bioenergy conversion, reporting energy yields ranging from 14.5 to 22.8 GJ per ton of dry biomass. Specifically, anaerobic digestion and gasification technologies were the most efficient pathways, achieving conversion efficiencies of 65–78% for biogas production and 55–67% for syngas generation [32].

Furthermore, co-firing biomass with coal in industrial boilers was reported in 5 studies, providing supplemental energy to palm oil mills with thermal efficiencies of 52–61% and CO_2 emission reductions of 20–28% compared to conventional fuel use [33]. Waste-to-energy systems using palm kernel shells (PKS) demonstrated electricity generation capacities ranging from 1.2 to 4.5 MW per facility, with a capacity factor of 72–78% [34].

Biofuel applications were highlighted in 12 studies, with biodiesel production from palm oil mill effluent (POME) and empty fruit bunches (EFB) yielding 210–320 liters per ton of biomass [35]. Advances in enzymatic pretreatment, co-fermentation, and microbial consortia increased lipid extraction efficiency by 15–22% compared with conventional alkaline transesterification [36]. Pilot-scale biorefineries demonstrated a combined biofuel and bioproduct output of approximately 1,200 tons annually, representing a 30% increase in biomass valorisation relative to earlier industrial implementations [37].

Emerging applications in bioplastics and value-added chemicals were identified in 10 articles, with production capacities ranging from 0.5 to 3.2 tons per day in laboratory and semi-industrial scales [38,39]. Polyhydroxyalkanoates (PHA) synthesized from palm oil by-products exhibited thermal stability between 160–175°C and mechanical strength comparable to conventional commercial polymers, while polylactic acid (PLA) composites achieved tensile strengths of 52–65 MPa and elongation at break of 6–9%, indicating potential for large-scale industrial adoption. Additionally, biochemicals such as furfural and levulinic acid produced from EFB and palm mesocarp fibers reached yields of 180–240 kg per ton of feedstock [40,41].

Collectively, these findings illustrate a diversification of industrial applications, moving beyond traditional energy generation toward integrated biorefinery approaches, which combine multiple value streams: energy, chemicals, and materials within a single facility. Industrial valorisation adoption rates were reported to be 45–60% in Southeast Asia and 25–35% in European pilot projects [42,43].

Regulatory Frameworks and Standards

The second major theme emerging from the SLR is the pivotal role of regulatory frameworks and international standards in guiding the industrial adoption of biomass valorisation. Among the 30 reviewed studies, 14 focused on policies, certification schemes, and sustainability standards, with Southeast Asia, particularly Indonesia and Malaysia, being the primary focus in 60% of these publications [44,45].

The Indonesian Sustainable Palm Oil (ISPO) standard and the Malaysian Sustainable Palm Oil (MSPO) certification collectively cover approximately 85% of certified plantations, ensuring compliance with national sustainability requirements. The Roundtable on Sustainable Palm Oil (RSPO), cited in 10 studies, acts as a global reference framework, influencing over 20 million tons of palm oil annually and providing traceability and sustainability metrics [46,47]. Despite these frameworks, 9 studies noted gaps in harmonization, particularly regarding biomass valorisation metrics, indicating that only 40–50% of industrial biomass processing fully complies with recognized sustainability criteria [48].

Emerging technical standards also influence industrial practices. ISO 13065 (Sustainability criteria for bioenergy) and ASTM D6751 (Biodiesel Fuel Standard) were cited in 6 studies as critical for quality assurance and international trade compliance [49]. Compliance with EU Renewable Energy Directive (RED II) standards directly affected adoption rates, with European and North American facilities showing increases of 15–22% upon certification. Additionally, adherence to Life Cycle Assessment (LCA) and Environmental Product Declarations (EPD) was reported to improve investment attractiveness and reduce operational risk by 10–18% [50].

These findings underscore that regulatory and standardization frameworks not only drive environmental and social compliance but also provide tangible economic and operational incentives for industry actors, influencing project scalability and international market access.

Market Trends and Economic Potential

Market trends and economic viability constitute the third theme identified in the SLR. Twenty of the 30 reviewed studies examined market size, investment potential, and growth trajectories for palm oil biomass valorisation. The global biomass-to-bioenergy market is projected to grow at a compound annual growth rate (CAGR) of 7.4% between 2022 and 2028, reaching an estimated USD 18.6 billion by 2028 [51]. Bioplastics derived from palm oil biomass are anticipated to expand from 0.7 million tons in 2021 to 1.5 million tons by 2026, representing a CAGR of 14.2% [52].

The review revealed that commercialization is driven by technological efficiency, government incentives, and market demand for sustainable products. Approximately 65% of industrial-scale valorisation projects reported positive net present values (NPV) and internal rates of return (IRR) exceeding 12%, indicating strong economic feasibility [53]. Pilot-scale biorefineries converting EFB and palm kernel shells into bioethanol and biogas demonstrated revenue increases of 25–32% compared with conventional waste-disposal strategies [54].

Regional disparities were observed: Southeast Asia remains the dominant producer, contributing 54% of global palm oil biomass feedstock, whereas Europe serves as the largest consumer market for value-added products, accounting for 40–45% of international trade in palm oil-derived bioenergy. Emerging markets in North America, the Middle East, and East Asia are projected to account for an additional 20–25% of global demand by 2026, driven by renewable energy mandates and sustainability incentives [55].

Technological improvements, such as enzymatic pre-treatment and integrated co-fermentation, were reported to enhance commercial yields by 10–18%, while operational efficiencies in pilot biorefineries improved feedstock-to-product conversion rates from 62% to 77% [56]. These data suggest that economic feasibility is closely tied to both technological advancement and compliance with regional sustainability and quality standards.

Sustainability and Circular Economy Practices

Sustainability and circular economy integration comprise the fourth key theme. Sixteen studies explicitly quantified environmental impacts, including reductions in greenhouse gas (GHG) emissions, improvements in resource efficiency, and increases in waste diversion rates. Biomass-to-energy pathways, particularly anaerobic digestion, were reported to reduce CO_2-equivalent emissions by 28–36% relative to conventional biomass burning or landfill disposal [57].

Integrated biorefineries converting biomass into multiple outputs, biofuel, bioplastics, and fertilizers, enhanced material efficiency by 42–55%, directly contributing to circular economy objectives [58].

Lifecycle assessment (LCA) data from 9 studies indicated that overall energy consumption decreased by 18–24% compared to fossil-based production systems [59]. Waste-to-value strategies achieved biomass recovery rates averaging 68%, resulting in reduced environmental burden and additional revenue streams from secondary products. Furthermore, adoption of anaerobic digestion combined with nutrient recovery systems increased fertilizer output by 15–20%, reducing reliance on synthetic fertilizers and closing nutrient loops [60].

Environmental indicators, such as Global Warming Potential (GWP) and Acidification Potential (AP), demonstrated reductions of 20–32% and 15–25%, respectively, for fully integrated biorefineries [61]. These improvements were consistently correlated with higher adoption of standards-compliant operations and advanced processing technologies, reinforcing the interconnected benefits of technological, regulatory, and market-driven drivers in achieving sustainability objectives.

Across all 30 studies, industrial applications were concentrated in bioenergy (60%) and biofuels (40%), while emerging sectors such as bioplastics (33%) and biochemicals (20%) showed increasing adoption. Policy adherence was variable, with only ~50% of biomass valorisation projects complying fully with recognized international sustainability standards. Market growth projections ranged from 7–14% annually across bioenergy, bioplastics, and bioproduct markets. Environmental metrics indicated reductions of 28–36% in GHG emissions, improvements of 42–55% in material efficiency, and biomass recovery rates of approximately 68%.

The quantitative synthesis emphasizes that industrial adoption, economic feasibility, and sustainability outcomes are interdependent: technological innovations drive efficiency gains, regulatory compliance supports market access, and circular economy practices enhance environmental and economic performance. This integrative perspective offers a holistic understanding of the current state of palm oil biomass valorisation and provides evidence-based guidance for future industrial and policy development.

Discussion

The systematic literature review conducted in this study provides a comprehensive understanding of how industrial applications, regulatory frameworks, market opportunities, and sustainability practices collectively shape the adoption, scalability, and impact of palm oil biomass valorisation. By synthesizing evidence from 30 peer-reviewed articles published between 2019 and 2025, this review highlights emerging trends and provides strategic insights for industry and policy. The discussion below is organized around the four key dimensions identified in the research question, followed by an integrated analysis linking these dimensions to adoption, economic-environmental outcomes, and scalability.

Industrial Applications and Technological Adoption

Industrial applications of palm oil biomass constitute the backbone of valorisation initiatives, determining the feasibility and economic viability of converting residues into value-added products. Across the reviewed literature, bioenergy generation remains the most widely implemented application, with 60% of the studies reporting on anaerobic digestion, gasification, and co-firing technologies [62]. Biogas yields from POME and EFB are reported between 65–78%, translating to 14.5–22.8 GJ per ton of dry biomass [63]. Gasification of PKS and mesocarp fibers achieves syngas conversion efficiencies of 55–67%. These high efficiencies underscore the technological readiness of bioenergy applications, explaining their widespread adoption in industrial settings.

Beyond energy, biofuel production from palm oil residues, including biodiesel and bioethanol, has demonstrated significant potential. Reported yields range from 210–320 liters per ton of biomass when employing enzymatic pre-treatment and co-fermentation techniques [64]. Pilot-scale biorefineries producing combined biofuel and bioproduct outputs of 1,200 tons annually represent a 30% improvement in biomass utilisation compared to earlier industrial trials. The literature also indicates emerging trends in bioplastics and biochemical production, with polyhydroxyalkanoates (PHA) and polylactic acid (PLA) achieving thermal stability of 160–175°C and mechanical properties comparable to those of petroleum-based polymers [65]. Production capacities in laboratory and semi-industrial settings range from 0.5 to 3.2 tons per day, suggesting scalability potential.

Several studies emphasize that technological adoption is not uniform globally. Southeast Asia leads in production due to abundant feedstock, while Europe exhibits the highest adoption of high-value applications, such as bioplastics and bio-based chemicals, driven by policy incentives and market demand for sustainable materials [66]. The literature indicates that successful adoption is linked to the integration of multiple valorisation pathways, often within biorefinery approaches, that maximise yield and economic returns while enhancing environmental performance.

Regulatory Frameworks and Standards

Regulatory frameworks and sustainability standards are critical enablers of industrial adoption, influencing both the scalability of technologies and market access. National standards, such as the Indonesian Sustainable Palm Oil (ISPO) and Malaysian Sustainable Palm Oil (MSPO), regulate plantation management, industrial processing, and downstream biomass utilisation, covering approximately 85% of certified plantations in the region. International frameworks, particularly the Roundtable on Sustainable Palm Oil (RSPO), extend regulatory influence by guiding production practices, ensuring environmental compliance, and facilitating access to global markets [67].

The literature highlights a positive correlation between compliance with these frameworks and industrial adoption rates. Facilities adhering to ISPO, MSPO, or RSPO standards demonstrate higher efficiency in biomass utilisation, improved market access, and lower environmental risk [68]. Nevertheless, gaps exist in standard harmonization, particularly concerning biomass valorisation metrics, with only 40–50% of industrial biomass processing meeting comprehensive sustainability criteria. Emerging standards for bioenergy (ISO 13065) and biodiesel quality (ASTM D6751) further support compliance and trade facilitation, especially in Europe and North America, where renewable energy directives incentivize sustainable operations [69].

Regulatory frameworks also influence investment decisions. Stricter compliance is associated with higher technology adoption and access to premium markets for bio-based products. Studies report that firms investing in certified biomass valorisation projects achieve internal rates of return (IRR) exceeding 12% and positive net present values (NPV), highlighting the economic incentive of regulatory adherence. Thus, policy mechanisms and standards serve as both enablers and drivers for the scale-up of biomass valorisation technologies.

Market Opportunities and Economic Impact

Market dynamics play a central role in shaping the adoption and scalability of palm oil biomass valorisation. Global projections indicate that the biomass-to-bioenergy sector is expected to grow at a compound annual growth rate (CAGR) of 7–9% from 2022 to 2028, reaching an estimated USD 18.6 billion. Similarly, the market for bioplastics derived from palm oil biomass is projected to increase from 0.7 million tons in 2021 to 1.5 million tons by 2026, representing a CAGR of 14.2% [70].

The literature emphasizes that commercialization is driven by a combination of technological efficiency, regulatory incentives, and demand for sustainable products. Approximately 65% of industrial-scale valorisation projects report positive financial outcomes, with pilot-scale biorefineries converting EFB and PKS into bioethanol and biogas, generating 25–32% higher revenue compared to conventional disposal strategies [71]. Geographically, Southeast Asia dominates feedstock supply (54% of global production), while Europe represents the largest consumer of value-added products, accounting for 40–45% of international trade in palm oil-derived bioenergy [72].

Emerging trends include integrating bio-based product portfolios into industrial operations, creating multiple revenue streams, and reducing economic risks associated with single-product dependency [73]. Furthermore, technology-driven cost reductions, including advances in enzymatic pre-treatment, co-fermentation, and integrated biorefinery processes, enhance profitability while supporting sustainability objectives [74]. These findings suggest that market opportunities, when coupled with technological innovation and regulatory compliance, are pivotal in driving adoption and scaling biomass valorisation.

Sustainability Practices and Circular Economy Integration

Sustainability practices and circular economy principles are increasingly recognized as essential factors influencing industrial adoption, economic returns, and environmental impact [75]. Sixteen of the reviewed studies quantify environmental outcomes, reporting reductions in greenhouse gas emissions of 28–36% through anaerobic digestion, biorefinery, and waste-to-value strategies [76]. Material efficiency improvements range from 42–55%, while average biomass recovery rates reach 68%, contributing to resource efficiency and circular economy objectives [77].

Lifecycle assessment (LCA) results demonstrate energy savings of 18–24% relative to conventional fossil-based production systems, with corresponding reductions in global warming potential (20–32%) and acidification potential (15–25%) [78]. Additionally, nutrient recovery from POME and other residues enhances fertilizer output by 15–20%, decreasing reliance on synthetic inputs [79]. Collectively, these practices not only mitigate environmental impact but also improve economic feasibility by reducing input costs and creating additional revenue streams.

The literature indicates that integrating circular economy principles is a key determinant of long-term adoption. Industrial operations that implement multi-output biorefineries and comprehensive waste-to-value systems are better positioned to achieve scalability and resilience, particularly in regions with stringent regulatory requirements and high market demand for sustainable products.

Synthesis and Emerging Trends

When considered together, industrial applications, regulatory frameworks, market dynamics, and sustainability practices reveal a synergistic influence on adoption, scalability, and economic and environmental outcomes. Quantitative synthesis from the reviewed studies shows that 60% of valorisation initiatives focus on bioenergy, 40% on biofuels, 33% on bioplastics, and 20% on biochemicals [80]. Approximately 50% of industrial projects fully comply with recognized sustainability standards, with non-compliance often linked to early-stage or pilot operations [81]. Market growth indicators, including CAGR and projected revenue, indicate strong economic viability, while environmental metrics confirm significant reductions in emissions and gains in resource efficiency.

Emerging trends identified in the literature include:

- Integration of multi-output biorefineries to maximize yield and diversify revenue streams.
- Stronger regulatory alignment and international standard adoption to facilitate market access and compliance.
- Technology-driven cost optimization, including enzymatic pre-treatment, co-fermentation, and process intensification.
- Circular economy adoption, combining energy recovery, material reuse, and nutrient recycling to enhance sustainability and resilience.
- These trends collectively inform future industrial strategies and policy development, indicating that successful biomass valorisation requires simultaneous attention to technology, regulation, market conditions, and sustainability performance.

The findings of this review carry several important implications for policymakers, industry stakeholders, and researchers. First, regulatory frameworks and sustainability standards play a pivotal role in enabling the adoption of industrial applications and ensuring environmental compliance, suggesting that harmonization and expansion of standards specific to biomass valorisation are necessary. Second, integrating circular economy principles enhances economic and environmental outcomes, underscoring the need to invest in multi-output biorefinery infrastructure. Third, market-driven incentives, coupled with technological innovation, can accelerate industrial adoption and improve the scalability of biomass valorisation initiatives.

For future research, several directions are recommended. Studies should focus on developing standardized metrics for biomass valorisation efficiency and environmental impact, enabling comparative assessments across regions and industrial scales. Additionally, investigations into policy harmonization and cross-border trade implications could inform global strategies to promote sustainable biomass utilisation. Research on emerging high-value products derived from palm oil biomass, including specialty chemicals and biopolymers, is also warranted to enhance economic viability and diversify market opportunities. Finally, longitudinal studies examining the long-term environmental and economic impacts of integrated biorefinery systems would provide robust evidence to guide industrial scaling and policy development.

Conclusion

The systematic literature review on industrial applications and global trends in palm oil biomass valorisation provides a comprehensive synthesis of evidence from 30 peer-reviewed articles published between 2019 and 2025. The findings indicate that palm oil biomass is increasingly being converted into high-value products through diversified technological pathways, including bioenergy, biofuels, bioplastics, and biochemical production. Bioenergy and biofuel applications remain the most mature, with reported conversion efficiencies of 55–78% and energy yields of 14.5-22.8 GJ per ton of dry biomass, highlighting both technological readiness and industrial feasibility. Emerging bioplastics and biochemical production demonstrate scalability potential, with laboratory and semi-industrial outputs ranging from 0.5 to 3.2 tons per day, suggesting promising avenues for economic and environmental value creation.

Regulatory frameworks and sustainability standards play a critical role in shaping the adoption and scalability of biomass valorisation initiatives. Compliance with national standards such as ISPO and MSPO, as well as international frameworks such as RSPO, ISO 13065, and ASTM D6751, is associated with greater efficiency, improved market access, and reduced environmental risk. However, gaps in standard harmonization persist, particularly in metrics specific to biomass utilization, with only 40–50% of industrial processing meeting comprehensive sustainability criteria. The integration of regulatory compliance with industrial practice not only facilitates market participation but also encourages environmentally responsible valorisation strategies.

Market analyses reveal robust economic potential for the valorisation of palm oil biomass. The biomass-to-bioenergy sector is projected to grow at a compound annual growth rate of 7–9%, while bioplastics derived from biomass are expected to expand at a 14.2% CAGR, reflecting strong demand for sustainable, value-added products. Industrial operations implementing integrated biorefineries and multi-product portfolios achieve higher revenue, reduce economic risk, and demonstrate positive financial performance, with internal rates of return exceeding 12% and pilot-scale operations reporting revenue improvements of 25–32%. Geographic patterns indicate that Southeast Asia remains the primary feedstock supplier, while Europe and North America represent key markets for value-added bioproducts, illustrating the global relevance of sustainable biomass utilization.

Sustainability practices, particularly the adoption of circular economy principles, significantly enhance both environmental and economic outcomes. Biomass-to-energy pathways, integrated biorefineries, and nutrient recovery strategies contribute to 28–36% reductions in greenhouse gas emissions, 42–55% improvements in material efficiency, and an average biomass recovery rate of 68%. Lifecycle assessment results further demonstrate energy savings of 18–24% relative to conventional fossil-based production systems, with reductions in global warming and acidification potential of 20–32% and 15–25%, respectively. These findings underscore the importance of circular economy integration for long-term scalability, resilience, and sustainable performance.

Emerging trends identified in this review suggest that the future of palm oil biomass valorisation will rely on integrated multi-output biorefineries, stronger regulatory alignment, technology-driven cost optimisation, and comprehensive circular-economy adoption. These trends collectively indicate that successful industrial implementation depends on the simultaneous consideration of technological innovation, policy compliance, market dynamics, and environmental stewardship.

Overall, the evidence demonstrates that palm oil biomass valorisation can achieve substantial economic, industrial, and environmental benefits when implemented in a coordinated and sustainable manner. By leveraging technological advancements, adhering to regulatory and sustainability standards, identifying market opportunities, and integrating circular-economy practices, industrial stakeholders can maximize the value of palm oil residues while minimizing environmental impact. These findings provide actionable insights for policymakers, investors, and industry practitioners, supporting informed decision-making and guiding future research and industrial strategy development.

JEL Classifications: Q16 (Agricultural R&D/Technology), Q28 (Government Policy), Q56 (Environment & Development), L52 (Industrial Regulation), and O33 (Technological Change: Diffusion)

Contribution/Originality: This systematic review synthesizes evidence on palm oil biomass valorisation by integrating industrial technologies with policy/standards (ISPO/MSPO/RSPO), market opportunities, and sustainability/circular-economy metrics. It consolidates fragmented research, maps dominant and emerging applications, and identifies cross-cutting gaps (standardized metrics, policy harmonization, scalable biorefineries).

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