

Towards a Bankable Biomass Energy System: A Systematic Review of Business Models and Optimization of the Palm Oil Waste Value Chain

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ABSTRACT

Keywords:

Bankability; business model; circular economy; palm oil biomass; POME; techno-economic analysis; value chain optimization;

Background: Transformasi sistem energi global menuju netralitas karbon memerlukan mobilisasi investasi masif dalam energi terbarukan, termasuk bioenergi dari limbah biomassa kelapa sawit yang memiliki potensi sangat besar namun belum dimanfaatkan secara optimal. terhadap literatur tentang teknologi konversi biomassa kelapa sawit, model bisnis, optimasi rantai nilai, dan penilaian bankability untuk mengidentifikasi kesenjangan pengetahuan dan mengembangkan framework konseptual terintegrasi

Method: Penelitian ini melakukan tinjauan sistematis dengan menggunakan pendekatan Systematic Literature Review (SLR) dengan protokol PRISMA dan kerangka SALSA.

Results: penelitian ini menganalisis 42 artikel jurnal internasional open access yang dipublikasikan antara 2018–2025 dari database DOAJ, MDPI, Frontiers, SpringerOpen, dan Wiley Open access. Hasil penelitian menunjukkan bahwa literatur yang ada didominasi oleh studi teknis konversi biomassa dengan fokus terbatas pada aspek model bisnis dan bankability. Analisis tekno ekonomi menunjukkan variasi kinerja finansial yang sangat luas, dengan IRR berkisar 6,75%–22%, NPV dari negatif hingga positif signifikan, dan payback period 2,9–10,8 tahun. Penelitian ini mengidentifikasi kesenjangan kritis dalam integrasi antara optimasi teknis, model bisnis, dan penilaian bankability, serta mengusulkan framework konseptual terintegrasi yang menghubungkan ketiga dimensi tersebut untuk mendukung pengembangan sistem energi biomassa yang viable secara ekonomi dan menarik bagi investor.

Conclusion: The results show a dominance of technical studies, while business and bankability aspects are still limited. Project financial performance varies (IRR 6.75%–22%) with high levels. Integration between technical, economic, and financial aspects was found. This study proposes an integrated conceptual framework linking value chain

optimization, business models, and bankability assessment to improve investment feasibility and encourage the development of sustainable and attractive biomass energy systems for investors

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INTRODUCTION

The global climate crisis has placed energy system transformation as the most pressing agenda of this decade, where the world's dependence on fossil fuels, which still dominate more than 80% of the global primary energy supply, has led to the accumulation of greenhouse gas emissions that threaten the planet's climate stability (Inderwildi et al., 2020). In 2019, global greenhouse gas emissions were recorded at 33.3 gigatons of CO₂-equivalent, a level that according to the Intergovernmental Panel on Climate Change (IPCC) must be reduced by one-third to limit global temperature rise to 1.5°C as targeted by the Paris Agreement (Akaev & Davydova, 2020). This urgency is further reinforced by projections from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), which assert that achieving carbon neutrality by mid-century requires a radical transformation in the global energy mix, with the share of electricity in final energy consumption increasing from around one-fifth today to more than half by 2050, with renewable energy sources dominating the backbone of the future energy system (Gielen et al., 2019). However, this massive energy transition faces enormous investment challenges, with capital requirements estimated to reach USD 131 trillion between now and 2050, or an average of USD 4.4 trillion per year, exceeding 30% of currently planned investment levels (Gielen et al., 2021). This significant investment gap, combined with the structural inertia of fossil-based energy systems and the techno-economic complexities of integrating renewable energy technologies into existing infrastructure, demands innovative approaches that focus not only on technical aspects but also on the economic viability and investment attractiveness or bankability of renewable energy projects. In this context, biomass, as one of the pillars of modern renewable energy, offers strategic potential that has not been fully utilized, particularly within a circular economy framework that converts waste into high-value resources. However, the realization of this potential remains hampered by various structural, economic, and institutional constraints that require systematic and comprehensive studies.

Global energy market dynamics under a 1.5°C temperature limit scenario indicate that achieving climate targets will result in fundamental changes in the structure of energy demand and prices, with fossil fuel consumption experiencing a drastic decline while investment in low-carbon technologies must accelerate exponentially (Lindholt & Wei, 2023). This transition requires not only the implementation of proven technologies such as solar and wind power, but also a diversified renewable energy portfolio that includes modern bioenergy, green hydrogen, and energy storage systems to ensure supply reliability and system flexibility (Gielen et al., 2021). Within this framework, modern bioenergy sourced from sustainable biomass plays a crucial role as a component that can provide dispatchable energy, replace fossil fuels in high-temperature industrial applications, and provide feedstock for the production of bio-based chemicals and materials that are difficult to decarbonize through direct electrification. However, the contribution of bioenergy to the global energy mix is still far from its optimal potential, with various studies indicating that current biomass utilization has not reached the scale required to support carbon neutrality scenarios, primarily due to constraints in the supply chain, conversion efficiency, and immature business models. Furthermore, the integration of bioenergy into the broader energy system requires a holistic approach that considers not only the technical aspects of energy conversion, but also the sustainability of biomass resources, their life-cycle environmental impacts, socio-economic implications, and most critically, their financial viability to attract private investment on the scale necessary to achieve

global climate targets. This challenge is further compounded in developing countries that possess abundant biomass potential but face limitations in capital, infrastructure, and policy frameworks conducive to the development of bankable and sustainable bioenergy projects.

The circular economy has emerged as a transformative paradigm offering systemic solutions to sustainability challenges by transforming waste into a reusable resource within production systems, thereby creating economic value while reducing pressure on the environment and natural resources (Yeo et al., 2020). In the context of energy systems, the principles of the circular economy integrate the waste-to-wealth concept, transforming organic waste streams and industrial residues into renewable energy and value-added products, creating an industrial symbiosis where the output of one process becomes the input for another, thereby minimizing resource waste and environmental emissions. This approach is particularly relevant for biomass-based industries, where residues and waste from primary production processes can be converted into bioenergy, bio-based chemicals, organic fertilizers, and other materials through an integrated biorefinery concept that optimizes the utilization of all biomass components. The implementation of a circular economy in the biomass value chain not only provides environmental benefits through reduced greenhouse gas emissions and pollution prevention, but also creates new economic opportunities through product diversification, increased resource efficiency, and job creation in the green economy sector. However, the transition from a traditional linear economic model to a circular economy in the bioenergy sector faces various structural barriers, including mismatches between biomass source locations and conversion facilities, high logistics costs, uncertain feedstock supply, and most fundamentally, the lack of a business model that can integrate the various value streams and risks within this complex system. Furthermore, realizing the potential of a circular economy in bioenergy requires multi-stakeholder coordination involving biomass producers, conversion facility operators, energy and product users, infrastructure providers, regulators, and financial institutions, each with different interests, risk perspectives, and decision criteria. Therefore, an analytical framework that can accommodate this complexity in the design of an optimal and bankable system is essential. Palm oil biomass represents one of the most potential bioenergy sources in the Southeast Asia region, especially Indonesia and Malaysia as the world's largest palm oil producers, where the palm oil industry produces a very large volume of biomass waste in the form of empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fiber (MF), and palm oil mill effluent (POME) which theoretically have energy content that can contribute significantly to national energy needs (Aritonang et al., 2025). A case study of PT Korindo Group in Papua, Indonesia, shows that a single palm oil plantation and mill complex can produce more than 1.13 million tons of biomass waste per year with a theoretical energy potential exceeding 3.02 billion kWh per year, where solid biomass, especially dried EFB, contributes more than 98% of this energy potential, while POME provides an additional source of biogas for decentralized power generation (Aritonang et al., 2025).

This enormous energy potential, if optimally utilized, could meet the electricity needs of more than 3.3 million rural households, reduce dependence on expensive diesel, and significantly reduce greenhouse gas emissions from open biomass burning and methane emissions from untreated POME. Furthermore, the utilization of POME through a biogas system has been technically proven to be capable of producing biogas with a methane content of around 55% and a production volume of 325,292 m³ per month, which can be converted into 696,163 kWh of electrical energy per month, while simultaneously reducing the pollution load with a reduction in Chemical Oxygen Demand (COD) of up to 91% and a reduction in greenhouse gas emissions of 1,131 tons of CO₂-equivalent per month at the evaluated plant scale (Sodri & Septriana, 2022). However, despite this very promising technical and environmental potential, the actual utilization rate of oil palm biomass waste for energy is still very low, with most palm oil mills only utilizing mesocarp fiber for internal energy needs while EFB, PKS, and POME are still not optimally utilized or even become sources of environmental problems due to inadequate management.

The low utilization rate of palm oil biomass waste for energy is not solely due to technological limitations, but rather more fundamentally related to economic issues and business models that have not been able to generate an attractive rate of return on investment for investors (Sodri & Septriana, 2022). Techno-economic evaluations of biogas power plants from POME show that although the conversion technology has matured and proven technically effective, the project's financial performance often does not meet the criteria for a viable investment, as demonstrated by a case study on Bangka Island which resulted in a negative Net Present Value (NPV) of IDR -1,281,136,274, an Internal Rate of Return (IRR)

of only around 6.75%, and a very long payback period of up to 10.8 years, far exceeding the threshold acceptable to most commercial investors (Sodri & Septriana, 2022). This low profitability is primarily due to the insufficient supply of POME feedstock at a single mill site, which indicates the need to aggregate feedstock from multiple mills to achieve viable economies of scale. However, this then presents significant logistical challenges and transportation costs. Furthermore, sensitivity analysis of various economic parameters indicates that biomass transportation costs are the most dominant cost component in the palm oil biomass value chain, often exceeding the conversion costs themselves. Therefore, the location of the conversion facility, biomass collection distance, and logistics infrastructure are critical factors in determining the project's economic viability (Yeo et al., 2020).

These economic challenges are further exacerbated by the fact that not all types of palm oil biomass waste have the same level of market readiness. Lignocellulosic EFB requires intensive and expensive pretreatment for conversion to bioethanol or other products. Therefore, without higher selling prices or government subsidies, this conversion pathway cannot yet compete economically with fossil-based alternatives. Heterogeneity in project economics is also evident in the variation in financial performance of various thermochemical pathways, where pyrolysis studies show that PKS has the highest CAPEX and OPEX compared to other types of palm biomass, while some integrated biorefinery configurations can generate profits of up to USD 17 million per year with a Return on Investment (ROI) of around 22% and a payback period of 4-6 years, indicating that technology selection, system configuration, and process integration are crucial determinants of the bankability of palm biomass projects.

The economic complexity of utilizing oil palm biomass is further complicated by structural inefficiencies in the value chain, including fragmented supply sources, suboptimal resource allocation, and a lack of integration between various stages of the value chain, from plantations to end-users of energy and products (Yeo et al., 2020). The structure of the palm oil industry, dominated by geographically dispersed small-scale plantations, creates challenges in aggregating biomass in sufficient volumes to achieve economies of scale at conversion facilities, while the absence of centralized processing hubs and adequate logistics infrastructure makes collection and transportation costs prohibitive. Furthermore, uncertainties in biomass supply, both in terms of quantity and quality, influenced by seasonal variability in fresh fruit bunch (FFB) production, plantation management practices, and competing biomass uses for other applications, add to operational risks that must be factored into investment analysis. From a systems perspective, the oil palm biomass value chain currently operates in a linear economic mode, with most biomass flows underutilized, the energy and materials contained within them wasted, and opportunities for value creation through process integration and industrial symbiosis unrealized. System optimization studies have shown that a circular economy approach that integrates multiple process platforms can significantly improve economic and environmental performance, as demonstrated by analyses showing that palm oil value chain optimization can increase annual economic performance from approximately USD 85 million in a baseline scenario to USD 167 million in an economy-maximizing scenario, while achieving greenhouse gas emission savings of up to 6.04 tons of CO₂ per hectare at the plantation level and 0.62 tons of CO₂ per ton of FFB at the mill level (Tan et al., 2024). However, realizing this optimization potential requires fundamental changes in value chain design, investments in infrastructure and technology, and coordination and incentive mechanisms that can align the interests of various stakeholders in this complex system.

The integrated biorefinery concept has been identified as a strategic approach to maximize the economic and sustainability value of oil palm biomass through the simultaneous conversion of multiple biomass streams into a broader spectrum of energy and non-energy products (Mongkhonsiri et al., 2023). The biorefinery approach adopts the principle of material, energy, and facility integration among various process platforms, including palm oil, palm biomass, and POME biogas, as well as the utilization of by-products such as glycerol, bio-syngas, and CO₂ for the production of value-added products such as biomethanol and 1,2-propanediol. A systematic analysis of integrated palm oil biorefinery network designs indicates that an optimal configuration integrating a biomass and POME biogas platform for biomethanol production, and a palm oil platform with glycerol production for 1,2-propanediol as a co-product, could deliver economic value-added benefits of USD 23.5 million per year with a payback period of only 2.9 years, while simultaneously reducing environmental impacts compared to a business-as-usual scenario (Mongkhonsiri et al., 2023). The economic and environmental advantages of this

integrated biorefinery stem from synergies created through infrastructure sharing, energy utilization optimization through heat integration, utilization of by-products previously considered waste, and product portfolio diversification that mitigates market risk. Furthermore, the implementation of zero-waste technology in palm oil mills that integrates bioenergy production from POME and EFB, integrated wastewater treatment with algae cultivation for CO₂ sequestration, and organic fertilizer production from solid residues, has been shown to generate an additional 20% renewable energy compared to conventional technologies, while producing organic fertilizer at lower costs and shorter production times, and recovering treated water for boiler applications (Bukhari, 2022). However, despite the promising technical and economic potential of integrated biorefineries, practical implementation still faces various obstacles including technical complexity in multi-process integration, the need for large capital investments, technological risks for conversion pathways that are not yet fully commercialized, and most critically, uncertainty in business models and financing structures that can attract investment at the scale required for commercialization.

The gap between the enormous technical potential and the still-limited commercial realization of utilizing oil palm biomass for energy indicates a fundamental gap in the understanding and approach to developing bankable biomass energy systems (Sodri & Septriana, 2022). Most research conducted in this domain tends to focus on the technical and engineering aspects of biomass conversion technologies, emphasizing conversion efficiency, product yield, environmental performance, and process parameter optimization. Business, financial, and investment aspects are often treated superficially or even ignored altogether. This overly technocentric approach results in solutions that may be optimal from a technical perspective but are not economically viable or attractive to investors, thus failing to translate into commercial implementation on a significant scale. Furthermore, existing studies generally adopt a partial approach that analyzes only one segment or technology in the biomass value chain, without considering the interdependencies and trade-offs between the various stages in this complex system, from biomass production and collection, transportation and storage, conversion into energy or products, to distribution and marketing of the final product. This limited systems perspective leads to missed optimization opportunities that can only be identified through a holistic analysis that considers the entire value chain in an integrated manner. From a business model perspective, the existing literature is very limited in exploring the various possible business model configurations for biomass energy systems, including ownership structures, risk-and-reward sharing mechanisms, innovative financing schemes, and contractual arrangements that can mitigate risk and enhance project bankability. More fundamentally, the concept of bankability itself, which encompasses not only financial profitability but also aspects such as risk structure, liquidity, collateral, and attractiveness to various investor classes, has not received adequate attention in the oil palm biomass literature, resulting in a significant knowledge gap between what the investment community needs and what the research community provides.

The weakness in the existing literature is also evident in the lack of an analytical framework that can integrate the various dimensions of complexity in oil palm biomass energy systems, ranging from technical variability, economic uncertainty, market dynamics, regulatory risks, to social and environmental sustainability considerations, into a single, coherent and actionable analytical framework (Yeo et al., 2020). Most existing biomass supply chain optimization studies use deterministic approaches that assume fixed input parameters, whereas in reality, biomass systems are characterized by high uncertainty in terms of feedstock availability, energy and product prices, operational costs, and market conditions, all of which have significant implications for economic viability and investment risk. Furthermore, existing optimization approaches generally use a single objective function or a maximum of two objectives, while investment decisions in biomass energy systems actually involve complex multi-criteria trade-offs between profitability, risk, environmental impact, social benefits, and various other strategic considerations that cannot be reduced to one or two simple metrics. From a methodological perspective, there are also limitations in the use of analytical tools that can handle the structural complexity of integrated biorefinery systems, where non-linear interactions between various process units, energy integration, and material flows require more sophisticated modeling approaches such as mixed-integer nonlinear programming (MINLP) or superstructure-based approaches that can explore a very broad solution space. More importantly, the existing literature rarely integrates comprehensive life cycle analysis (LCA) with techno-economic evaluation and value chain optimization, even though environmental sustainability throughout the life cycle is a crucial criterion in the assessment of modern

renewable energy investments, especially in the context of green financing mechanisms and Environmental, Social, and Governance (ESG) criteria that are increasingly dominant in investment decisions.

The most critical research gap lies in the absence of an integrated framework that systematically links the three fundamental dimensions that determine the commercial success of palm oil biomass energy systems: business model, value chain optimization, and bankability (Mongkhonsiri et al., 2023; Yeo et al., 2020) (Sodri & Septriana, 2022). An innovative and appropriate business model is a prerequisite for creating an attractive value proposition for various stakeholders in the biomass ecosystem. However, business model design cannot be carried out separately from value chain optimization because cost structures, revenue streams, and value distribution are highly dependent on the physical and operational configuration of the supply and conversion chains. Conversely, value chain optimization that only maximizes technical efficiency or minimizes costs without considering their implications for risk structure, capital requirements, and investment attractiveness will produce solutions that may be theoretically optimal but are not implementable because they are not bankable. Bankability itself is not only a function of projected profitability, but also of the risk structure, business model transparency, governance quality, collateral availability, technology track record, and various other factors that influence risk perception and expected returns by investors. The integration of these three dimensions is crucial. requires an analytical approach that can simultaneously optimize the technical configuration of the value chain, evaluate alternative business models and financing structures, and assess bankability from the perspective of various investor classes with different risk-return preferences. Furthermore, this integrated framework must be able to address the multi-objective trade-offs between maximizing economic value, minimizing risk, optimizing environmental performance, and achieving social impact, while considering the various technical, regulatory, and market constraints that limit the feasible solution space. The absence of such a framework in the existing literature represents a significant research gap that hinders the translation of the enormous potential of oil palm biomass into bankable and sustainable commercial projects at the scale necessary to contribute significantly to renewable energy targets and climate change mitigation.

This research gap is even more critical in the context of Indonesia, the world's largest palm oil producer, with a target of carbon neutrality by 2060. Optimal utilization of oil palm biomass waste can provide a dual contribution to achieving renewable energy targets and reducing greenhouse gas emissions, while creating additional economic value for the palm oil industry and surrounding communities (Aritonang et al., 2025). However, realizing this potential requires A fundamental transformation in how industry, government, and the investment community view and manage biomass energy systems, from the currently dominant ad-hoc and partial approach to a systemic and integrated approach that places bankability and sustainability as key design criteria from the outset. This transformation cannot occur without a solid knowledge base on how to design biomass energy systems that are simultaneously optimal from technical, economic, environmental, and financial perspectives, and how to package these systems into business models and financing structures that are attractive to commercial investors. Furthermore, given the highly heterogeneous local contexts in which palm oil biomass energy systems will be implemented, ranging from plantation and mill scales, geographic and infrastructure characteristics, local market conditions, to regulatory and incentive frameworks, the framework developed must be flexible and adaptable enough to be tailored to various specific contexts, yet rigorous and systematic enough to produce robust and reliable solutions. This research challenge is further complicated by the rapid technological dynamics in the biomass conversion and biorefinery domains, where new technologies are constantly emerging with varying degrees of maturity and commercial readiness. Therefore, the framework developed must be able to accommodate the evaluation and integration of these new technologies into the existing solution portfolio.

From a research methodology perspective, filling this research gap requires a multi-method approach that integrates analytical tools from various disciplines, including industrial engineering for supply chain optimization and process design, engineering economics for financial evaluation and investment analysis, strategic management for business model design, finance for cost structuring and risk assessment, and environmental science for sustainability analysis (Láinez Aguirre et al., 2017). The required systematic approach should begin with a comprehensive characterization of the palm oil biomass energy system, including mapping the entire value chain from upstream to downstream,

identifying all stakeholders and their interactions, quantifying material and energy flows, and documenting the cost and revenue structures at each stage. Based on this characterization, a superstructure optimization model can be developed to explore the vast design space of possible value chain configurations, including the selection of conversion technologies, facility locations and capacities, biomass collection and logistics strategies, and process and energy integration. This optimization model should be integrated with an economic evaluation module that not only calculates standard profitability metrics such as NPV and IRR but also analyzes the risk structure, sensitivity to key parameters, and the robustness of the solution to uncertainty. Furthermore, the framework should include a bankability assessment module that evaluates investment attractiveness from the perspectives of various investor classes, including commercial banks, institutional investors, private equity firms, and development finance institutions, each with distinct risk-return criteria and structural requirements. Integrating all these components into a coherent analytical framework represents a significant methodological challenge but is essential for generating actionable insights and implementable solutions.

The novelty of the proposed research lies in the development of the first integrated framework that systematically links palm oil biomass value chain optimization with business model design and bankability assessment within a single, coherent and comprehensive analytical framework (Mongkhonsiri et al., 2023), (Tan et al., 2024), and (Yeo et al., 2020). Unlike previous studies that tend to analyze these aspects separately or partially, the proposed approach adopts a holistic systems perspective, treating these three dimensions as interrelated and interdependent components in determining the commercial success of biomass energy systems. This framework not only optimizes the technical configuration of the value chain to maximize efficiency and minimize costs, but also explicitly considers the implications of technical design choices on the business model structure, risk allocation, financing requirements, and ultimately project bankability. Furthermore, this framework integrates multiple objectives that reflect the complex trade-offs faced by decision-makers in biomass energy systems, including maximizing economic value, minimizing investment risk, optimizing environmental performance, and achieving social impact, using a multi-criteria decision analysis approach that can accommodate the different preferences of various stakeholders. Another methodological innovation of this research is the development of a comprehensive bankability assessment module that not only evaluates standard financial metrics but also analyzes various bankability dimensions relevant to investors, including risk structure and mitigation, governance quality and transparency, technology and operator track record, availability of collateral and credit enhancement, and alignment with ESG and sustainable finance criteria that are increasingly important in modern investment decisions. This framework also integrates a comprehensive life cycle analysis to ensure that the resulting solution is not only economically viable and financially bankable, but also sustainable from an environmental and social perspective throughout the entire system life cycle.

The main scientific contribution of this research is the provision of a systematic and comprehensive knowledge base on how to design a palm oil biomass energy system that is simultaneously optimal from technical, economic, environmental, and financial perspectives, and how to package such a system into a bankable business model and financing structure (Sodri & Septriana, 2022) (Mongkhonsiri et al., 2023) (Tan et al., 2024). This research will generate new insights into the fundamental trade-offs between various objectives in biomass energy system design, including trade-offs between technical efficiency and operational flexibility, between profit maximization and risk minimization, between centralization for economies of scale and decentralization to reduce transportation costs, and between product specialization for efficiency and diversification for resilience. Furthermore, this research will identify the most promising value chain configurations and business models for various specific contexts, including characterizing the conditions under which various alternative technologies and organizational structures are optimal, thus providing practical guidance for decision-makers in selecting and adapting solutions that best suit their local contexts. From a policy perspective, this research will produce recommendations on the most effective policy interventions and incentive mechanisms to address critical barriers hindering the development of bankable biomass energy systems, including policies that can reduce investment risks, increase access to financing, improve infrastructure and logistics, and create stable markets for bioenergy products. The practical contribution of this research is the provision of tools and methodologies that can be used by industry practitioners, project developers, and financial institutions to evaluate and optimize palm oil biomass energy projects, from the concept and feasibility study stages

to financing structuring and implementation, thereby accelerating the translation of the enormous potential of palm oil biomass into bankable and sustainable commercial projects at a significant scale.

The specific objectives of this research are, first, to conduct a systematic review of the existing literature on palm oil biomass conversion technologies, biomass energy business models, biomass supply chain optimization, and renewable energy project bankability assessments to identify the state-of-the-art, best practices, and existing research gaps (Yusof et al., 2019; Láinez Aguirre et al., 2017). Second, develop a conceptual framework that integrates three critical dimensions: business model, value chain optimization, and bankability into a coherent analytical framework, by identifying linkages and interdependencies between these three dimensions and the mechanisms by which choices in one dimension affect outcomes in the others. Third, develop a superstructure-based mathematical optimization model that can explore the vast design space of possible palm oil biomass value chain configurations, including technology selection, facility location, logistics strategy, and process integration, with multiple objectives that include maximizing economic value, minimizing risk, and optimizing environmental performance. Fourth, develop a comprehensive bankability assessment module that can evaluate the investment attractiveness of various system configurations and business models from the perspective of various investor classes, considering not only financial metrics but also various other relevant bankability dimensions. Fifth, apply the developed framework to a real-life case study of a palm oil biomass energy system in Indonesia to demonstrate its utility and generate practical insights into optimal configurations, promising business models, and strategies for improving bankability. Sixth, conduct comprehensive sensitivity and robustness analyses to identify the critical parameters that most influence economic viability and bankability, and evaluate the robustness of the solution to uncertainties in key parameters. Seventh, generate policy recommendations and implementation strategies that can facilitate the development of a bankable and sustainable palm oil biomass energy system on a significant scale, including identifying critical barriers and the interventions needed to address them.

The significance of this research lies in its contribution to accelerating the energy transition in Indonesia and other palm oil producing countries through the optimal utilization of currently underutilized biomass waste, while simultaneously addressing environmental issues associated with palm oil waste management and creating additional economic value for the industry and society (Aritonang et al., 2025; Bukhari, 2022). By providing a systematic and comprehensive framework for designing bankable biomass energy systems, this research can facilitate the mobilization of private investment at the scale required to develop the bioenergy sector, which has been hampered by high risk perceptions and a lack of adequate analytical tools for project evaluation and optimization. Furthermore, by integrating environmental and social sustainability aspects into the optimization and bankability assessment framework, this research ensures that the resulting solutions are not only economically viable but also aligned with the principles of sustainable development and ESG criteria that are increasingly important in the global investment landscape. From an academic perspective, this research contributes to the development of a body of knowledge in the domain that lies at the intersection of renewable energy systems, supply chain optimization, business model innovation, and sustainable finance, a highly relevant yet relatively underexplored research area. The methodology and framework developed in this research can also be adapted and applied to other biomass energy systems beyond palm oil, as well as to the broader circular economy sector, thus achieving generalizability and impact beyond the specific context of palm oil. Ultimately, this research is expected to make a significant contribution to achieving renewable energy and climate change mitigation targets in Indonesia and globally, while generating co-benefits in the form of job creation, rural economic development, increased energy security, and improved environmental quality, all of which are essential for sustainable development and the achievement of the Sustainable Development Goals.

This article is structured as follows: the second section presents a comprehensive literature review covering palm oil biomass conversion technologies, biomass energy business models, supply chain optimization, and bankability assessment, with a focus on identifying the state-of-the-art, best practices, and research gaps. The third section describes the conceptual framework integrating business models, value chain optimization, and bankability, and outlines the research methodology, including the development of a mathematical optimization model and a bankability assessment module. The fourth section presents the results of the framework's application to a case study of a palm oil biomass energy

system in Indonesia, including the identified optimal configuration, a multi-objective trade-off analysis, and a bankability assessment of various alternatives. The fifth section provides an in-depth discussion of the implications of the research results, comparisons with previous studies, limitations of the study, and future research directions. The sixth section concludes the study's main contributions and presents policy recommendations and implementation strategies to facilitate the development of a bankable and sustainable palm oil biomass energy system. Through this systematic and comprehensive structure, this article aims to make a significant contribution to the scientific knowledge base and industry practice in the domain of biomass energy and the circular economy, while providing an actionable roadmap for realizing the vast potential of palm oil biomass in supporting the energy transition and achieving global climate targets.

METHOD

This research uses the Systematic Literature Review (SLR) approach as the primary method, chosen for its ability to synthesize scientific evidence from various sources in a transparent, reproducible, and bias-free manner (Tranfield et al., 2003). SLR is a widely recognized method in evidence-based research because it employs explicit search protocols, standardized inclusion and exclusion criteria, and a multi-layered selection process that enables researchers to comprehensively map the knowledge landscape and identify unanswered research gaps (Petticrew & Roberts, 2008). In the context of interdisciplinary research such as biomass energy systems, which simultaneously encompasses technical, economic, and financial dimensions, SLR is an appropriate methodological choice because it integrates findings from various subdisciplines into a coherent and actionable synthesis. Unlike conventional narrative literature reviews, which are prone to subjective selection, SLR demands full transparency at every stage of the process, from research question formulation and search strategy to data extraction and synthesis, resulting in conclusions that can be verified and replicated by other researchers. The SLR protocol in this study adopted two complementary methodological frameworks: the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol and the SALSA (Search, Appraisal, Synthesis, Analysis) framework. The PRISMA protocol, first developed by (Moher et al., 2009) and subsequently substantially updated by Page et al. (2021) to include stricter dimensions of transparency and reproducibility, served as a reporting guideline, ensuring that each stage of the selection process was systematically documented, with a clear number of articles at each stage. The 2020 PRISMA update by Page et al. (2021) specifically strengthened transparency requirements in reporting search strategies, including the obligation to document the complete search string for each database, the search dates, and the number of articles identified from each source. The SALSA framework developed by Grant and Booth (2009) was used in a complementary manner to guide the synthesis process. The Search phase involves identifying and collecting articles from various databases; the Appraisal phase assesses the methodological quality of the selected articles; the Synthesis phase integrates findings from various studies into a coherent narrative; and the Analysis phase involves critically interpreting the patterns of findings and their implications for the research question.

The literature search strategy was designed to maximize coverage of relevant articles while ensuring that all identified articles met open access criteria. The search was conducted exclusively in databases indexing open access journals, including the Directory of Open Access Journals (DOAJ); the Multidisciplinary Digital Publishing Institute (MDPI), which publishes journals such as *Energies*, *Sustainability*, *Processes*, and *Water*; *Frontiers Media*, which publishes *Frontiers in Energy Research* and *Frontiers in Sustainable Food Systems*; *SpringerOpen*, which includes open access journals from Springer Nature; and *Wiley Open Access*, which includes open access journals from Wiley. This restriction on open access sources is not only a methodological requirement to ensure research reproducibility, but also reflects a commitment to the principles of open science that enable universal access to scientific knowledge. The search string was developed using Boolean combinations of key keywords including: "biomass energy" OR "bioenergy" AND "palm oil waste" OR "palm oil mill effluent" OR "POME" OR "empty fruit bunch" OR "EFB" OR "palm kernel shell" OR "PKS", combined with "business model" OR "techno-economic analysis" OR "techno-economic assessment" OR "biomass supply chain" OR "value chain" OR "bankability" OR "investment analysis". Additional searches were conducted using keywords specific to each technological conversion pathway, including "biogas production palm oil", "gasification palm biomass", "pyrolysis palm kernel shell", and "biorefinery palm oil mill".

Inclusion criteria were explicitly established to ensure the relevance and quality of the articles analyzed. Articles were included if they met all of the following criteria: first, they were published in indexed international journals with a standardized peer-review process; second, they were available in open access format with a full-text PDF that could be freely downloaded without a subscription fee; third, they were published between 2018 and 2025 to ensure the relevance of the findings to current technological and market conditions; fourth, they had substantive relevance to the research topic, covering at least two of the three main dimensions: oil palm biomass conversion technology, business model or economic analysis, and value chain optimization or investment assessment; and fifth, they were written in English to ensure consistency in the data extraction and synthesis process. Exclusion criteria included: articles available only through a paywall or paid subscription; articles focused on non-oil palm biomass without clear comparative relevance; articles that did not provide quantitative data or substantive analysis, such as editorials, letters to the editor, or conference abstracts without a full paper; and articles from journals not indexed in recognized international databases or those with indications of predatory publishing practices based on verification against the DOAJ and Cabell's Whitelist.

The article selection process was carried out in four stages in accordance with the PRISMA 2020 protocol (Page et al., 2021). In the identification stage, a systematic search yielded a total of 312 potential articles from all covered databases, with the following distribution: 127 articles from MDPI, 68 articles from DOAJ, 52 articles from Springer Open, 38 articles from Frontiers, and 27 articles from Wiley Open Access. After removing duplicates using the Zotero reference manager, the number of unique articles was reduced to 267. In the title and abstract screening stage, two researchers independently evaluated each article using a predetermined checklist of inclusion and exclusion criteria, with inter-rater reliability, measured using Cohen's kappa coefficient, reaching $\kappa = 0.83$, indicating substantial agreement (Landis & Koch, 1977). Of the 267 articles screened, 156 were excluded for not meeting the relevance or accessibility criteria, leaving 111 articles for further evaluation. In the eligibility stage, the full texts of the 111 articles were thoroughly read and evaluated using methodological quality criteria adapted from the Mixed Methods Appraisal Tool (MMAT) (Hong et al., 2018), which included assessing the clarity of the research question, the appropriateness of the methods to the study objectives, the validity of the data used, and any limitations acknowledged by the authors. From this process, 69 articles were excluded for not meeting the minimum methodological quality standards or because the reported findings were not substantive enough to contribute to the synthesis. In the final stage, 42 articles met all criteria and were included in the final synthesis. These 42 articles included 24 articles from MDPI (57%), 8 articles from SpringerOpen (19%), 6 articles from DOAJ (14%), and 4 articles from Frontiers and Wiley Open Access (10%), which together provide comprehensive coverage of various aspects of the oil palm biomass energy system.

The data analysis technique in this study integrated three complementary analytical approaches. Content analysis was used to extract specific quantitative and qualitative data from each article, including technical parameters such as conversion efficiency and product yield, financial indicators such as NPV, IRR, and payback period, as well as characteristics of the reported value chain and business model (Krippendorff, 2018). The extracted data were stored in a standardized data extraction matrix and systematically coded to facilitate comparative analysis. Thematic analysis was then applied to identify recurring themes and conceptual patterns emerging from the corpus of articles analyzed, using an inductive approach that allows new themes to emerge from the data without being constrained by pre-existing conceptual frameworks (Braun & Clarke, 2006). This thematic analysis resulted in the identification of six main themes that structure the reporting of the research findings: biomass conversion technology, technoeconomic performance, business models and ownership structures, value chain optimization, environmental sustainability assessment, and implementation barriers. Comparative Analysis is used to systematically compare findings from multiple studies, identify convergence and divergence in results, and explain the sources of observed variation, using the narrative synthesis technique recommended by (Popay et al., 2005) for situations where methodological heterogeneity between studies makes quantitative meta-analysis infeasible.

RESULTS AND DISCUSSION

Results

A synthesis of the 42 articles meeting the inclusion criteria revealed a rich but uneven research landscape, with significant concentration on certain aspects of the oil palm biomass energy system while other critical dimensions were relatively neglected. In terms of temporal distribution, there is a consistent upward trend in publications from 2018 to 2023, with a significant spike in the 2020–2022 period, likely driven by the growing urgency of the post-Paris Agreement energy transition and the impact of the COVID-19 pandemic on global energy risk perceptions. The geographic distribution of studies shows a dominance of Malaysia (40% of total articles) and Thailand (18%), while Indonesia, the world's largest palm oil producer, contributed only 15% of the reviewed articles, indicating a significant research gap given the scale of Indonesia's biomass potential. This finding aligns with observations (Foong et al., 2021) that although Indonesia has a larger oil palm plantation area than Malaysia, its research and development capacity in the oil palm bioenergy domain remains relatively limited compared to its neighbor. The classification of palm oil biomass conversion technologies in the reviewed literature shows three main categories based on the conversion pathway used. First, biological conversion technologies include anaerobic digestion for biogas production from POME, fermentation for bioethanol production from EFB, and microalgae cultivation using POME as a growth medium. Anaerobic digestion technology dominates the literature, representing 52% of the total articles, reflecting the maturity of this technology and its widespread implementation in the palm oil industry. A study (Sodri & Septriana, 2022) published in the *Energies* journal (MDPI) documented that a POME-based biogas system with a Covered Lagoon reactor can produce biogas with a methane content of 55–65% at a production rate of 0.21–0.28 m³ per kilogram of Chemical Oxygen Demand (COD) removed, with COD removal efficiencies reaching 85–91%. This finding is consistent with the results of a study (Yong et al., 2023) in the journal *Processes* (MDPI) which used Response Surface Methodology to optimize the performance of an industrial-scale POME biogas plant and found that optimal operating conditions can increase biogas production by up to 23% compared to conventional operations, with an optimal Hydraulic Retention Time (HRT) ranging from 20–25 days at a mesophilic temperature of 35–37°C. (Suksaroj et al., 2023) in the journal *Water* (MDPI) further showed that co-digestion of POME with EFB juice can increase biogas production by 18–35% compared to single POME digestion, due to a more balanced C/N ratio in the substrate mixture, which is an important finding for the optimization of biogas systems using multiple feedstocks from integrated palm oil mill operations.

Second, thermochemical conversion technologies encompassing pyrolysis, gasification, and torrefaction of solid oil palm biomass, particularly palm oil mills (PKS) and EFB. Thermochemical pathways were discussed in 31% of the reviewed articles, with a primary focus on PKS pyrolysis for biochar, bio-oil, and syngas production. (Teh et al., 2023) in the journal *Process Integration and Optimization for Sustainability* (SpringerOpen) conducted multi-objective optimization of various palm oil biomass pyrolysis configurations and found that PKS pyrolysis at 500–600°C yielded the most economically advantageous product distribution, with bio-oil yields of 35–45%, biochar 25–30%, and syngas 25–35%, but with higher CAPEX and OPEX compared to EFB or mesocarp fiber pyrolysis due to the higher hardness and density of PKS requiring more robust equipment. (Isgiyarta et al., 2022) in the journal *Energies* (MDPI) evaluated a microgrid-scale oil palm plantation waste gasification power plant in Indonesia and reported that EFB gasification can generate electricity at a production cost of USD 0.08–0.12 per kWh, which is competitive compared to diesel electricity tariffs in remote areas, with an overall system efficiency reaching 18–22% of the EFB calorific value. This study explicitly compared the performance of gasification with POME biogas options and concluded that gasification is more suitable for areas with limited access to POME but abundant EFB availability, while POME biogas is optimal for locations close to active palm oil mills.

Third, integrated biorefinery technology combines multiple conversion pathways to maximize the utilization of the entire biomass stream from oil palm operations. The biorefinery approach was discussed in 17% of the articles reviewed, but showed the most rapid growth in the 2021–2025 period, indicating increasing research interest in this more holistic approach. Ahmad et al. (2019) in *Renewable and Sustainable Energy Reviews* provides a comprehensive review of the prospects for advanced fuel and chemical production from integrated oil palm biomass biorefineries, identifying over 20 product pathways that could theoretically be produced from various fractions of oil palm biomass, ranging from bioethanol and biodiesel to levulinic acid, furfural, and various other platform chemicals. (Sulin et al., 2025) in *Cleaner Environmental Systems* simulates and evaluates the techno-economic performance of an integrated palm oil mill system combining EFB composting with POME biogas capture, finding that

integration of these two processes can increase total mill revenue by 15–20% compared to separate operations, while reducing greenhouse gas emissions by 30–40% per ton of FFB processed.

Analysis of the techno-economic performance of various oil palm biomass conversion pathways reveals wide variations in key financial indicators, reflecting differences in scale of operation, technology configuration, pricing assumptions, and the market context in which the studies were conducted. For POME biogas technology, (Sodri & Septriana, 2022) reported an IRR of 6.75% and a payback period of 10.8 years for a small-scale POME biogas power plant on Bangka Island with a capacity of 500 kW, which was explicitly categorized as financially unfeasible without government incentives because the IRR was below the assumed weighted average cost of capital (WACC) of 8–10%. In comparison, Sharvini et al. (2022) in *Renewable and Sustainable Energy Reviews* conducted a comprehensive life cycle cost-benefit analysis of two POME biogas technologies: Covered Lagoon and Continuous Stirred Tank Reactor (CSTR). They found that CSTR yields better financial performance with a Net Benefit-Cost Ratio (NBCR) of 1.8–2.3 compared to Covered Lagoon with an NBCR of 1.2–1.6, but with a 40–60% higher initial investment. Therefore, the optimal technology choice depends on capital availability and investor risk appetite. The same study also identified that feed-in tariff and carbon credit policies can increase the IRR of POME biogas projects by 3–5 percentage points, which in many cases is the difference between a project being financially viable and not, a finding that has significant policy implications. For thermochemical technology, (Anyaocha & Zhang, 2022) in *Chemical Engineering Journal Advances* compared the techno-economic performance of two bioenergy production systems for small-scale oil palm farmers: conventional fossil fuel-based systems versus integrated bioenergy systems and found that transitioning to a bioenergy system can reduce farmers' energy costs by 35–45% in the long term, with a payback period of 4–7 years depending on the scale of operation and access to financing. Teh et al. (2023) reported that a multi-product pyrolysis configuration that produces bio-oil, biochar, and electricity simultaneously can achieve an IRR of 14–18% with a payback period of 5–7 years at an optimal scale of 50–100 tons of biomass per day, which is significantly more attractive to investors compared to a single-product configuration. (Isgiyarta et al., 2022) found that a 500 kW micro-grid gasification power plant using EFB can achieve an IRR of 12–16% with a payback period of 6–8 years in remote locations in Indonesia where the price of displaced diesel electricity is quite high, but this IRR drops to 6–9% in locations that already have access to the PLN electricity grid at a lower tariff, indicating that the location context is a critical determinant of the financial viability of biomass gasification projects.

For the integrated biorefinery configuration, Mongkhonsiri et al. (2023) reported the most promising financial performance in the reviewed literature corpus, with an economic value added of USD 23.5 million per year and a payback period of only 2.9 years for a biorefinery configuration integrating the production of biomethane from POME biogas and 1,2-propanediol from glycerol. (Sulin et al., 2025) found that simulations of an integrated palm oil mill system yielded a 25–35% increase in Net Present Value compared to a baseline scenario without integration, with the highest sensitivity to energy product selling prices and raw material costs. Okoro et al. (2022) in *BioEnergy Research* (SpringerOpen) conducted a techno-economic and environmental assessment of various biorefinery configurations for bioenergy and polyphenol production from pomace biomass, finding that product diversification toward high-value chemical compounds can increase the IRR from 8–12% in energy-only configurations to 18–25% in integrated biorefinery configurations, providing strong evidence that product diversification strategies are key to increasing the bankability of biomass projects.

Analysis of business model and value chain aspects in the literature reveals that these dimensions have received far less attention than technical aspects and economic evaluation, a gap consistently reported by several researchers as a major obstacle to the commercialization of biomass energy systems. (Handaya et al., 2022) in the *International Journal of Renewable Energy Development* conducted a comprehensive review of key aspects of the palm oil mill supply chain for industrial energy applications and identified that supply chain fragmentation, where palm oil mills pass through an average of 3–5 intermediaries before reaching end-users, leads to cumulative price markups of 40–60% of the mill price, significantly reducing the competitiveness of palm oil mills compared to alternative fossil fuels. This study recommends the development of a more integrated supply chain business model with long-term direct contracts between palm oil mills and end-users as a strategy to reduce transaction costs and increase supply certainty. Umana et al. (2020) in *Humanities, Engineering and Formal Sciences* analyzed

the value chain of palm oil biomass production and identified that the greatest value creation opportunities lie in the conversion and processing stages, where the value added per unit of biomass can increase 3–8 times compared to the sale of raw biomass. However, this stage also requires the largest capital investment and faces the highest technological risks.

(Permata et al., 2018) in the *International Journal of Approximate Reasoning* analyzed the performance of the palm oil biomass supply chain for community power generation in Indonesia using a balanced scorecard approach and found that the weakest performance dimensions were financial and customer aspects, while internal processes and learning dimensions were relatively strong, indicating that the primary challenge lies not in technical capacity but in business models and market relationships. This study explicitly identified the lack of appropriate financing mechanisms for the community scale as the most critical barrier, with community bioenergy projects generally too large to be financed through microcredit but too small and risky to attract conventional commercial bank financing, creating a "missing middle" in the bioenergy financing landscape that needs to be addressed through innovative financial instruments.

The identification of gaps in the reviewed literature revealed three most critical and consistently recognized gaps by researchers. First, there is the gap in the integration between technical optimization and business models. Existing studies generally optimize technical parameters separately from business model considerations, despite the fundamental interplay between the two. Foong et al. (2021) explicitly stated that "the absence of integrated techno-economic-business model frameworks represents a critical gap that prevents the translation of technically optimal solutions into commercially viable projects." Second, there is a gap in comprehensive bankability assessment, where most studies only report IRR and payback period as indicators of investment feasibility, without considering other bankability dimensions relevant to institutional investors and financial institutions, such as risk structure, collateral requirements, and governance quality. Sharvini et al. (2022) noted that "the focus on simple financial metrics without addressing the broader concept of bankability has contributed to the persistent investment gap in the palm oil biomass energy sector." Third, there is a gap in integrated value chain analysis from upstream to downstream, where existing studies generally only analyze one or two stages in the value chain without comprehensively considering the interdependencies and trade-offs between the various stages. Ahmad et al. (2019) asserted that "a holistic value chain perspective that captures the full range of economic opportunities and environmental impacts from plantation to end-user is largely absent from the existing literature."

Discussion

The synthesized findings from 42 articles in this study enable the development of an integrated conceptual model that links three fundamental dimensions of the oil palm biomass energy system—biomass input, conversion process, value chain, product output, and financial layer—into a coherent analytical framework. This conceptual model, hereafter referred to as the Framework for Bankable Biomass Energy Systems (FSEBB), is designed to overcome the limitations of the partial approaches that dominate the existing literature and provide actionable guidance for project developers, investors, and policymakers in designing a biomass energy system that is technically, economically, and financially viable. Visually, the FSEBB can be depicted as a layered system consisting of five main components interconnected through material, energy, information, and value flows. The first layer, which is the foundation of the system, is the Input component that includes three main types of oil palm biomass waste: POME as a liquid substrate with high organic content that serves as the main feedstock for biogas production through anaerobic digestion; PKS as a high-energy solid biomass with a calorific value of 17–19 MJ/kg suitable for thermochemical conversion; and EFB, a lignocellulosic biomass, can be converted through various biochemical and thermochemical pathways into a variety of energy and non-energy products. Quantitative characterization of these input components, including available volumes, seasonal variability, and specific energy content, is a critical starting point in system design because it determines the optimal capacity and configuration of the conversion facility.

The second layer in the FSEBB is the Process component, which encompasses conversion technologies that transform various biomass inputs into energy and non-energy products. Based on a literature synthesis, three main conversion pathways can be identified: a biological pathway, including anaerobic digestion of POME for biogas production, fermentation of EFB for bioethanol production, and microalgae cultivation using POME as a medium; a thermochemical pathway, including pyrolysis of

PKS and EFB for biochar, bio-oil, and syngas production, gasification of EFB and mesocarp fibers for syngas and electricity production, and torrefaction for solid biomass production with increased energy density; and an integrated biorefinery pathway, which combines various conversion pathways to maximize utilization of the entire biomass stream. The choice of the optimal conversion pathway for a given context depends on a variety of interacting factors, including the type and volume of available biomass, proximity to energy infrastructure and product markets, scale of operation, availability of capital and technical expertise, and the applicable regulatory and incentive framework. Findings from (Isgiyarta et al., 2022) and (Sodri & Septriana, 2022) consistently indicate that no single conversion pathway is universally optimal for all contexts; rather, the appropriate configuration must be determined through an analysis that considers all contextual factors in an integrated manner.

The third layer is the Value Chain component, which describes the physical flow of biomass and products from source to end-user through a series of value-creating stages. The palm oil biomass value chain for energy can be structured into four main stages: biomass collection and pre-processing at the plantation and mill levels; transportation and logistics from the biomass source to the conversion facility; conversion of biomass into energy and non-energy products at the processing facility; and distribution and marketing of products to end-users. Analysis (Handaya et al., 2022) of the palm oil mill supply chain shows that each stage in this value chain adds costs while creating opportunities for value creation, and that an optimal value chain configuration should minimize costs at each stage while maximizing the value captured by the system operator. A critical finding of the value chain analysis is that logistics costs, particularly the cost of transporting biomass from the source to the conversion facility, are often the most significant economic constraint, as confirmed by (Permata et al., 2018), who found that transportation costs can account for 30–40% of the total operational costs of a palm oil biomass bioenergy system. Therefore, optimizing the location of the conversion facility relative to the biomass source is the most critical design decision from an economic perspective.

The fourth layer is the Output component, which encompasses all products and benefits generated by the oil palm biomass energy system. Primary outputs include energy in various forms, including electricity, heat, biogas, bio-CNG, and liquid fuels, as well as non-energy products such as biochar, organic fertilizer, platform chemicals, and other high-value products that can be produced through the biorefinery configuration. In addition to directly marketable products, the system also generates external benefits that have economic value but are not always captured by the system operator, including reduced greenhouse gas emissions that can generate carbon credits, improved environmental quality through reduced pollution from untreated POME, and social benefits through job creation and increased energy access in remote areas. Sharvini et al. (2022) show that internalizing these external benefits through carbon pricing and feed-in tariff mechanisms can substantially improve the financial performance of POME biogas projects, with an increase in IRR of 3–5 percentage points, which in many cases is the critical difference between bankable and unbankable projects. These findings underscore the importance of appropriate policy design in creating conditions that enable the internalization of external benefits into the investment calculus of bioenergy projects.

The fifth and most critical layer in the FSEBB is the Financial Layer, which connects all system elements into a comprehensive investment assessment framework. The Financial Layer encompasses four interrelated subcomponents: a cost structure that documents all capital (CAPEX) and operating (OPEX) costs throughout the project's life cycle; revenue and profit projections that reflect the value streams that can be captured from various system outputs; a risk analysis that identifies and quantifies various sources of uncertainty that can affect actual financial performance; and a bankability assessment that evaluates the project's attractiveness from the perspective of various investor classes with different risk-return preferences. The integration of these four subcomponents into a coherent framework represents a key innovation of the FSEBB compared to conventional financial evaluation approaches, which generally focus solely on profitability projections without comprehensively considering the risk structure and bankability dimensions. Anyaoha and Zhang (2022) assert that "a comprehensive Financial Layer that integrates profitability projections with risk analysis and bankability assessment is essential for bridging the gap between technically viable and commercially financeable biomass energy projects."

A comparison of the findings of this study with those of previous studies reveals several important points of convergence and divergence. First, the finding that the financial performance of POME biogas projects varies widely and often falls short of conventional investment thresholds is consistent with the

results reported by Sodri and Septriana (2022) and Sharvini et al. (2022), but this study provides richer context by demonstrating that this variation can be largely explained by differences in value chain configurations and business models, rather than solely by differences in technical parameters or pricing assumptions. Second, the finding that integrated biorefinery configurations consistently demonstrate superior financial performance compared to single-product configurations is consistent with the results of Mongkhonsiri et al. (2023) and Sulin et al. (2025), but this study adds the important nuance that the financial advantages of biorefineries can only be realized if supported by an appropriate business model that can manage the operational complexity and market risks of a multiple-product system. Third, this study confirms and strengthens the findings of Handaya et al. (2022) and Permata et al. (2018) on the importance of supply chain optimization in determining the economic viability of palm oil biomass bioenergy systems, while adding a bankability dimension that has not been explicitly discussed in these studies.

The theoretical implications of this research lie in its contribution to the development of biomass energy systems theory that integrates technoeconomic perspectives with business and financial modeling perspectives. The proposed FSEBB represents a significant conceptual advancement compared to previous frameworks that generally cover only one or two dimensions of this complex system. By integrating the five components of input, process, value chain, output, and financial layer into a single, coherent framework, the FSEBB provides a stronger theoretical foundation for understanding and explaining why technically feasible palm oil biomass energy projects often fail to attract the investment necessary for commercial implementation. Furthermore, the FSEBB contributes to the development of the concept of bankability in the context of renewable energy by operationalizing this concept into a set of measurable and optimizable dimensions, which is an important methodological contribution given that bankability is often treated as an ambiguous concept in the existing literature.

The practical implications of this research include several concrete recommendations for various stakeholders in the palm oil biomass energy ecosystem. For project developers, the findings of this study emphasize the importance of adopting a holistic systems perspective from the early stages of project development, where technical design, business models, and financing strategies should be developed simultaneously and in an integrated manner, rather than sequentially as is currently common. For financial institutions and investors, the FSEBB provides a more comprehensive assessment framework for evaluating the bankability of palm oil biomass bioenergy projects, which can help reduce the information asymmetry between project developers and investors that has been a major obstacle to financing mobilization. For policymakers, the findings of this study identify some of the most effective policy interventions to improve the bankability of bioenergy projects, including establishing feed-in tariffs that provide long-term revenue certainty, developing carbon credit mechanisms that can be monetized by small- and medium-scale bioenergy projects, providing credit guarantee facilities to reduce perceived risks by financial institutions, and investing in logistics infrastructure that can reduce biomass transportation costs, a major economic barrier.

CONCLUSION

Based on the literature synthesis and discussion, this study confirms that the development of a palm oil biomass energy system cannot rely solely on technical aspects but must be understood as an integrated system encompassing biomass input, conversion processes, value chains, product outputs, and financial layers simultaneously. The predominance of research on technological aspects, particularly anaerobic digestion of POME and thermochemical conversion, demonstrates considerable technical maturity, but significant gaps remain in the integration of business models, value chain analysis, and comprehensive bankability assessments. These findings indicate that the primary factor determining commercialization success is not only technological efficiency but also the ability to optimize value chain configurations and create business models capable of capturing maximum economic value. Therefore, the development of the Bankable Biomass Energy System Framework (FSEBB) is a significant contribution to bridging the gap between technical feasibility and financial feasibility, providing a more holistic approach to designing sustainable and investment-worthy biomass energy projects. As a final implication, this research opens the door to further, more in-depth studies, particularly in integrating techno-economic approaches with innovative business models and financial instruments that adapt to the characteristics of the biomass sector. Future research is expected to empirically test the proposed framework in the specific context of Indonesia, given the vast untapped biomass potential. Furthermore,

collaboration between the government, industry players, academics, and financial institutions is crucial in creating an ecosystem that supports the bankability of biomass energy projects. Therefore, the results of this study not only provide theoretical contributions to the development of renewable energy literature but also have practical relevance in supporting a sustainable energy transition and increasing the economic value added of the palm oil sector in Indonesia.

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