Biomass Energy in Malaysia: Feedstock Resources, Conversion Pathways, Supply Chains, Policy and Sustainability Perspectives

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DOI: https://doi.org/10.47772/IJRISS.2026.100900643

Received: 03 October 2026; Accepted: 08 October 2026; Published: 20 October 2026

ABSTRACT

Malaysia possesses a distinctive biomass-energy resource base because its agricultural and agro-industrial economy generates large quantities of oil-palm residues alongside other biomass streams such as forestry residues, rice residues, municipal and industrial organic wastes, bamboo and other lignocellulosic materials. The selected literature indicates that the central research problem is no longer simply whether biomass is available, but how biomass can be collected, converted, integrated, commercialised and governed in ways that deliver reliable energy and wider circular-economy value. This paper synthesizes the 100 references supplied for the study and organizes them around five interconnected dimensions: biomass-resource availability and characterization; conversion and valorisation technologies; supply-chain and system optimization; economic, environmental and social sustainability; and Malaysian policy, institutional and commercialization conditions. Attention is given to oil-palm biomass because the selected literature repeatedly identifies empty fruit bunches, trunks, fronds, fibres, shells, mill residues and palm-oil mill effluent as important components of Malaysia's biomass landscape. The literature also covers thermochemical routes such as combustion, co-firing, gasification, pyrolysis, torrefaction and hydrothermal carbonization, biological and biochemical routes, and higher-value biorefinery products. Across these pathways, logistics, moisture and feedstock heterogeneity, conversion efficiency, capital requirements, market development, policy coordination and environmental trade-offs emerge as interconnected determinants of deployment. The review proposes an integrated framework in which resource availability feeds technology selection, technology performance affects economics and environmental outcomes, and policy and supply-chain institutions condition the ability to scale projects. The paper concludes with research priorities for Malaysia, including integrated biomass hubs, improved logistics and traceability, better techno-economic and life-cycle assessment, digitalization, flexible policy instruments, and cascading use of biomass in which energy production is balanced with higher-value material and chemical applications.

Keywords: Biomass energy; Malaysia; oil palm biomass; bioenergy supply chain; circular economy; renewable energy policy

INTRODUCTION

The transition towards sustainable and low-carbon energy systems has become an increasingly important issue for countries seeking to balance economic development, energy security, environmental protection and resource efficiency. Within this transition, biomass occupies a distinctive position because it can simultaneously function as an energy resource, a source of renewable carbon and a feedstock for higher-value products. Unlike several intermittent renewable energy sources, biomass can be stored, transported and converted through a range of thermochemical, biochemical and biological processes. Consequently, biomass energy can contribute not only to renewable electricity and heat generation but also to the production of gaseous, liquid and solid fuels, chemicals, materials and other value-added products. The selected literature for this study demonstrates that

biomass utilization is increasingly being examined from an integrated perspective in which energy production is linked with waste management, circular-economy development, resource recovery and industrial decarbonization [1–10].

Malaysia presents a particularly important context for examining biomass energy because of the scale and diversity of biomass resources generated by its agricultural, agro-industrial and forestry activities. Among these resources, oil-palm biomass is especially significant. The Malaysian palm-oil industry generates multiple residue streams throughout cultivation, harvesting, milling and processing, including oil-palm trunks, oil-palm fronds, empty fruit bunches (EFB), mesocarp fibre, palm kernel shells, palm fibres and palm-oil mill effluent (POME). Rather than representing a single homogeneous resource, these materials differ substantially in moisture content, physical characteristics, chemical composition, availability, collection requirements and existing uses. The selected studies consequently examine oil-palm biomass not simply as waste but as a portfolio of feedstocks that can be directed towards energy generation, fuels, chemicals, biochar, materials and other applications [1, 2, 4–8, 11–18].

The scale and diversity of these residues create both opportunities and challenges. On one hand, the continuous generation of biomass from established agricultural and processing activities can provide a locally available renewable resource base. On the other hand, the spatial distribution of biomass, seasonal availability of certain residues, high moisture content, low bulk density, heterogeneous physical properties and transportation requirements can substantially affect the feasibility of biomass utilization. The selected literature therefore places considerable emphasis on biomass characterization, resource assessment, collection systems, transportation, facility location, supply-chain optimization and the efficient allocation of biomass among competing conversion pathways [1, 11, 19–25]. These considerations indicate that the development of biomass energy in Malaysia cannot be addressed solely by improving conversion technologies; the upstream resource and logistics system must also be considered.

Oil-palm biomass is particularly relevant to the Malaysian circular-economy agenda because many of its components can potentially be transformed into products with greater economic value than direct disposal or low-value utilization. Research included in the selected references investigates the conversion of oil-palm residues into biofuels, bioenergy, biochar, chemicals, bioproducts and other value-added materials [2, 26–35]. For example, research on zero-waste conversion, biorefinery concepts and the utilization of agricultural residues illustrates a shift from conventional waste-management approaches towards integrated resource recovery. In such systems, a biomass stream may be separated into different fractions and directed towards different products according to its physical and chemical characteristics. Energy generation can therefore become one component of a broader biomass valorisation strategy rather than the sole objective.

The technological diversity of biomass conversion further strengthens the importance of an integrated approach. Thermochemical technologies such as combustion, co-firing, gasification, pyrolysis, torrefaction and hydrothermal carbonization provide different routes for converting lignocellulosic materials into useful energy carriers and products [26–44]. Combustion can directly produce heat and electricity, while co-firing can facilitate the incorporation of biomass into existing energy systems. Gasification can convert biomass into synthesis gas that may subsequently be used for energy generation or further chemical conversion. Pyrolysis can produce bio-oil, gases and carbon-rich solid products, while torrefaction can improve the fuel characteristics and handling properties of biomass. Hydrothermal processes can provide an alternative route for wet biomass, potentially reducing the need for energy-intensive drying. The selected literature also includes biochemical and biological pathways involving biogas, bioethanol, biobutanol, bio-succinic acid and related products [2, 9, 28, 45–54].

The diversity of conversion pathways means that technology selection must be considered in relation to feedstock properties, energy demand, plant scale, market conditions and desired products. A technology that is appropriate for a dry and relatively uniform biomass stream may not be appropriate for a wet or highly heterogeneous feedstock. Similarly, a pathway designed primarily for energy production may have different economic and environmental implications from a biorefinery pathway producing several co-products. The

selected references therefore collectively suggest that biomass conversion should be evaluated through a systems perspective rather than by considering conversion efficiency as an isolated technical parameter [26–35, 40–54]. In addition to technological development, biomass supply-chain management is a central determinant of the feasibility of biomass energy projects in Malaysia. Biomass is often generated at numerous agricultural fields, plantations, mills and processing facilities rather than at a single centralized location. The movement of bulky and sometimes high-moisture biomass from dispersed sources to conversion facilities can introduce significant logistical requirements. Facility location, transportation routes, collection frequency, storage capacity, preprocessing, densification and inventory management can all influence the overall performance of a biomass system. The selected studies address these challenges using approaches including mathematical optimization, mixed-integer linear programming (MILP), location-routing models, simulation, genetic algorithms and other decision-support techniques [1, 19–25, 55–63].

The importance of supply-chain optimization is illustrated by studies examining the optimal operation and management of biomass facilities. Optimization models can be used to determine where biomass facilities should be located, how feedstocks should be allocated, which transportation routes should be used and how available biomass should be distributed among competing uses [1, 19–25]. Such approaches are particularly relevant in Malaysia because the value of a biomass resource can vary according to distance from a processing facility, moisture content, transportation cost, alternative uses and the technology selected. Consequently, biomass availability at the national level does not necessarily translate directly into economically recoverable biomass at the project level.

The challenge is further complicated by competition among alternative uses of biomass. Oil-palm residues may be used internally by mills, sold as fuel or feedstock, incorporated into agricultural systems, processed into materials, converted into chemicals or directed towards energy production. Some residues may also have environmental or agricultural functions that must be considered before they are diverted to commercial energy applications. The selected literature on biomass management, circular economy and resource allocation highlights the importance of recognizing these competing demands when assessing the sustainable energy potential of biomass [1, 11, 19, 24, 64–68]. Therefore, estimates of biomass-energy potential should distinguish between theoretical resource availability and the quantity that can realistically be collected and sustainably allocated to energy conversion.

Another important dimension is the expansion of biomass research beyond oil-palm residues. Although palm biomass is a major focus of the selected literature, Malaysia possesses other potentially important biomass resources, including forestry residues, agricultural wastes, bamboo and organic waste streams. Studies included in the reference set investigate bamboo utilization, forest and agricultural residues, tea waste and other lignocellulosic resources [69–77]. This broader resource base creates opportunities for diversification and could potentially reduce dependence on a single biomass supply chain. It also introduces additional challenges because different resources require different collection, preprocessing, storage and conversion strategies. A diversified biomass-energy system therefore requires resource-specific assessment rather than a uniform approach to all biomass materials.

The relationship between biomass energy and sustainability is also complex. Biomass is frequently categorized as renewable because biological resources can be replenished, but renewability alone does not establish that every biomass-energy pathway is environmentally sustainable. Environmental performance depends on feedstock origin, land-use implications, collection practices, transportation distances, preprocessing energy requirements, conversion efficiency, co-product treatment and the fate of carbon throughout the life cycle. The selected references include studies applying life-cycle assessment and related environmental evaluation approaches to biomass, biofuels, palm-based energy systems and competing renewable-energy technologies [78–84]. These studies indicate the importance of evaluating biomass pathways across their entire life cycle rather than considering only emissions at the point of energy conversion.

Life-cycle thinking is particularly important when comparing biomass with other renewable-energy options. A biomass pathway may generate renewable energy while simultaneously requiring transportation, preprocessing

and conversion infrastructure. Similarly, a biomass-derived fuel may have environmental advantages in one part of its life cycle while facing environmental burdens elsewhere in the supply chain. The selected literature includes comparative assessments of biodiesel and large-scale solar energy as well as other environmental assessments, demonstrating that renewable-energy technologies can have substantially different environmental profiles depending on the system boundary and functional unit adopted [80, 100]. This reinforces the need for project-specific and system-wide assessment rather than assuming that all renewable energy pathways have identical environmental benefits.

Economic feasibility represents another major determinant of biomass-energy deployment. Biomass projects require investment in collection systems, transportation, storage, preprocessing equipment, conversion technologies, utilities and supporting infrastructure. Their economic performance is also influenced by feedstock prices, plant utilization rates, energy prices, product markets, financing conditions and policy incentives. The selected studies examine techno-economic considerations associated with biomass conversion, biofuels, biorefineries, biochar and other biomass-derived products [34, 51, 57, 63, 69, 85–91]. These studies collectively support the view that technical feasibility does not automatically translate into commercial viability.

The economic dimension becomes particularly significant when biomass is used for higher-value applications. Energy-only systems may compete with lower-cost conventional energy sources or other renewable technologies, whereas integrated biorefineries can potentially distribute revenues across multiple products. Biomass can therefore be evaluated according to a cascading or multi-product approach in which material and chemical applications are considered alongside energy production. The selected literature on bio-succinic acid, biofuels, biochar, advanced carbon materials and other products demonstrates the broad range of value-creation pathways that can emerge from biomass [2, 27, 35, 42, 45, 49, 65, 88–94]. Such diversification may alter the economic structure of biomass projects by reducing dependence on a single energy product.

Policy and institutional conditions constitute an additional layer of the Malaysian biomass-energy system. The availability of biomass resources and appropriate technologies does not by itself guarantee large-scale deployment. Investment decisions are influenced by renewable-energy policies, electricity-market arrangements, incentives, financing mechanisms, environmental regulations, standards, technology support and the broader national energy-transition strategy. Several selected references examine Malaysian renewable-energy policy, energy scenarios, investment conditions, foreign direct investment, bilateral investment arrangements and policy reforms [64, 73, 84, 90, 95–100]. These studies indicate that biomass development must be considered within the wider institutional architecture governing Malaysia's transition towards a more diversified and lower-carbon energy system.

Policy coherence is especially important because biomass operates at the intersection of several sectors. Agricultural policy influences the generation and management of residues; energy policy affects electricity and fuel markets; environmental policy influences waste management and emissions; industrial policy shapes investment and manufacturing opportunities; and rural-development policies can influence local participation and employment. Consequently, biomass energy cannot be governed effectively through energy policy alone. Coordination among agricultural, environmental, industrial, investment and energy institutions is necessary to create conditions in which biomass resources can be mobilized efficiently and sustainably.

The social dimension of biomass energy is similarly interconnected with its economic and environmental dimensions. Biomass projects can create opportunities for rural employment, local enterprise development, technical skills and additional income associated with biomass collection and processing. At the same time, changes in biomass-use patterns can affect existing users and stakeholders. The establishment of centralized processing facilities may alter local supply chains, while large-scale biomass procurement can influence the distribution of benefits and costs among producers, processors, transport operators and communities. Although the selected literature is more heavily concentrated on technical, environmental and economic aspects than on social dimensions, its broader systems perspective suggests that stakeholder participation, institutional coordination and public acceptance should be incorporated into biomass-development strategies.

Digitalization is emerging as another potentially important component of biomass-energy development. The selected references include research related to digital technologies, Industry 4.0, traceability, monitoring and information-based biomass management [61, 66, 71, 96]. Digital systems can support the tracking of biomass from source to conversion facility, improve information on feedstock availability and quality, coordinate transportation, monitor storage conditions and support decision-making. For a geographically dispersed biomass sector, improved information availability could help reduce uncertainty concerning feedstock supply and facilitate more efficient coordination between producers, logistics providers and energy facilities.

The need for such coordination is reinforced by the variability of biomass resources. Unlike standardized fossil fuels, biomass properties can vary according to species, cultivation conditions, harvesting practices, storage duration and processing history. Moisture, ash content, particle size, chemical composition and energy content can influence handling and conversion performance. Consequently, reliable biomass characterization and quality-control systems are essential for maintaining stable conversion processes. The selected literature addressing biomass characterization and conversion reinforces the importance of understanding feedstock properties before selecting or scaling a particular technology [5–8, 12, 15, 29, 37, 41, 69–77].

Malaysia's biomass-energy opportunity should therefore be understood as a systems problem involving interconnected resource, technology, logistics, economic, environmental, social and policy dimensions. A narrow focus on individual conversion technologies risks overlooking constraints elsewhere in the value chain. For example, a technically efficient gasification or pyrolysis system may face difficulties if suitable feedstock cannot be supplied consistently and economically. Similarly, a large biomass resource may have limited commercial value if transportation costs are excessive or if the resource has competing higher-value uses. An environmentally attractive pathway may also require policy or market conditions that support investment and commercialization. The selected literature, when considered collectively, supports an integrated analytical framework in which each stage of the biomass value chain influences the performance of the others.

The literature also indicates an evolution from the traditional concept of biomass as a waste-to-energy resource towards the broader concept of biomass valorisation. Under a conventional waste-management model, the principal objective is to dispose of residues while recovering some energy. Under an integrated biorefinery and circular-economy model, the objective is to retain as much value as possible within the resource by producing a combination of energy, fuels, chemicals and materials. This distinction is important for Malaysia because the country's established agricultural and industrial biomass streams may support multiple markets simultaneously. The appropriate strategy may therefore depend on the relative value of products, local energy demand, resource characteristics, environmental constraints and policy priorities [2, 26–35, 42, 45, 88–94].

Against this background, the present paper examines the Malaysian biomass-energy sector through a structured synthesis of the 100 selected references provided for this study. The review focuses particularly on the relationship between biomass resources, conversion and valorisation technologies, supply-chain management, sustainability, economics and policy. Rather than treating these areas as independent topics, the paper considers how they interact to determine the feasibility and scalability of biomass-energy systems. Particular attention is given to oil-palm biomass because of its prominence within the selected literature, while other agricultural, forestry and lignocellulosic resources are incorporated to provide a broader representation of Malaysia's biomass landscape.

The paper seeks to move beyond a simple inventory of biomass resources or technologies. Its purpose is to synthesize the selected literature into an integrated understanding of how Malaysia can approach biomass as a multidimensional resource linking renewable energy, waste management, industrial development, circular economy and broader energy-transition objectives. The analysis subsequently examines biomass resources and feedstock characteristics, conversion and valorisation technologies, supply-chain and system optimization, economic and sustainability dimensions, and policy and commercialization conditions before proposing an integrated framework and identifying areas for future research.

Overall, the selected literature suggests that the future development of biomass energy in Malaysia depends not on the availability of biomass alone, but on the capacity to coordinate resources, technologies, logistics, markets, institutions and sustainability objectives. Biomass should therefore be considered as part of an interconnected value chain in which resource characteristics influence technology selection, technology selection influences economic and environmental performance, and policy and market conditions determine whether technically feasible systems can be implemented at commercial scale. This systems-oriented perspective provides the foundation for the subsequent analysis presented in this paper.

REVIEW METHODOLOGY AND ANALYTICAL FRAMEWORK

Review Design and Scope

This study adopts a structured critical/narrative review approach to synthesize evidence concerning biomass energy and biomass valorisation in Malaysia. The review is designed to integrate evidence across resource availability, conversion technologies, supply-chain management, economic and environmental performance, and policy and commercialization rather than to evaluate a single technology or feedstock in isolation.

The evidence base comprises 100 references selected for their relevance to Malaysian biomass resources, biomass conversion and valorisation, supply-chain and logistics systems, sustainability and environmental assessment, economic and techno-economic considerations, digitalization, and policy and institutional conditions. The purpose of the review is therefore not to estimate a pooled quantitative effect, but to identify recurring relationships, constraints, opportunities and evidence gaps across the Malaysian biomass value chain. The review is explicitly treated as a critical/narrative synthesis rather than a systematic review because the study does not claim to have undertaken a formal systematic database search and PRISMA-based screening process. The 100 references constitute the defined evidence base for the present synthesis. The review consequently emphasizes transparency in the organization, classification and interpretation of this evidence.

Literature Selection and Eligibility Principles

The reference set was examined according to four principal relevance criteria. First, a reference was considered relevant when it addressed biomass resources, biomass residues, biomass conversion, biomass-derived products or biomass supply chains. Second, studies addressing Malaysian biomass systems, Malaysian energy or policy conditions, or feedstocks and technologies demonstrably relevant to Malaysia were prioritized. Third, studies were retained when they contributed evidence to at least one of the analytical dimensions established for the review. Fourth, studies were excluded from the analytical synthesis when their subject matter did not provide a meaningful connection to biomass utilization, biomass systems, sustainability, technology, supply chains or the Malaysian policy and commercialization context.
The final evidence base contains 100 references. Because these references constitute a defined set supplied for the review rather than the outcome of a newly executed database-search process, the present study does not report fabricated database hit counts, duplicate-removal numbers or PRISMA exclusion statistics. Instead, the review provides an explicit thematic classification and analytical rationale for the 100-reference evidence base.

Evidence Coding and Thematic Classification

Each reference was classified according to its principal contribution to the review. Where a study addressed more than one topic, it could contribute evidence to multiple dimensions. Five interconnected dimensions were used:

Biomass-resource availability and characterization – including feedstock type, quantity, physical and chemical characteristics, spatial distribution, recoverability, competing uses and resource sustainability. Conversion and valorisation technologies – including combustion, co-firing, gasification, pyrolysis, torrefaction, hydrothermal conversion, anaerobic digestion, biofuels, biochemical conversion, biochar, advanced materials and integrated biorefinery approaches.

Supply-chain and system optimization – including collection, transportation, storage, preprocessing, facility location, routing, inventory management, multi-feedstock systems, optimization models, digitalization and traceability.

Economic, environmental and social sustainability – including techno-economic feasibility, capital and operating requirements, product markets, life-cycle impacts, greenhouse-gas emissions, resource efficiency, employment, stakeholder effects and competing sustainability objectives.

Policy, institutional and commercialization conditions – including renewable-energy policy, incentives, regulations, investment conditions, standards, market development, institutional coordination, technology deployment and commercialization.

The coding process was used to identify both the dominant subject of each reference and the connections between dimensions. For example, a study examining biomass collection through an optimization model was classified primarily under supply-chain and system optimization but could also provide evidence concerning economic and environmental performance. Similarly, a study examining a conversion technology was interpreted in relation to the feedstock characteristics, logistics requirements, economic implications and environmental consequences reported or discussed in the study.

Biomass Resources And Feedstock Characteristics

Overview of Biomass Resources in Malaysia

Malaysia possesses a diverse biomass resource base arising primarily from its agricultural, plantation, forestry and agro-industrial activities. Among these resources, oil-palm biomass occupies a particularly important position because of the extensive development of the palm-oil industry and the large number of residues generated throughout the cultivation, harvesting and milling processes. The selected literature demonstrates that these residues include oil-palm trunks, oil-palm fronds, empty fruit bunches (EFB), mesocarp fibre, palm kernel shells, palm fibres and palm-oil mill effluent (POME), each of which has different physical and chemical characteristics and therefore different potential applications [1–18].

The significance of Malaysia's biomass resources extends beyond the quantity of material generated. Biomass represents a renewable carbon resource that can potentially be incorporated into energy systems, biofuel production, biochemical manufacturing, material production and circular-economy applications. Several of the selected studies consequently investigate biomass utilization from a broader perspective than conventional waste disposal. The conversion of oil-palm residues into energy, chemicals, fuels and other value-added products demonstrates the potential for transforming agricultural residues into productive resources [2, 26–35].

However, the existence of a large biomass resource does not necessarily mean that the entire resource is technically or economically available for energy production. The practical utilization of biomass is influenced by its location, availability, moisture content, physical characteristics, collection requirements, transportation distance, competing uses and conversion technology. Consequently, biomass-resource assessment needs to distinguish between the total quantity generated and the fraction that can realistically be recovered and supplied to a conversion facility [1, 19–25].

Oil-Palm Biomass as a Major Feedstock

The oil-palm industry represents one of the most important sources of biomass considered in the selected literature. Biomass is generated at multiple stages of the oil-palm value chain, creating a distributed resource base that can potentially support different conversion pathways. The selected studies examine the utilization and characterization of several major oil-palm residues, including trunks, fronds, EFB, fibres, shells and mill-derived residues [1–18].

The diversity of these residues is important because they cannot be treated as a single standardized feedstock. Oil-palm trunks and fronds are generated primarily in plantation areas, whereas EFB, mesocarp fibre and palm kernel shells are closely associated with milling and processing operations. POME represents a substantially different biomass stream because it is a liquid organic residue requiring biological or other suitable treatment and conversion processes. The location and physical form of each residue therefore influence its collection, transportation, storage and conversion requirements.

The selected literature illustrates the range of possible uses for these resources. Oil-palm residues have been investigated for direct energy generation, thermochemical conversion, gasification, pyrolysis, biochar production, biofuel production, biochemical conversion and higher-value material applications [2, 26–54]. This diversity suggests that resource allocation should be based on the characteristics and potential value of individual biomass streams rather than assuming that all residues should follow the same utilization pathway.

Empty Fruit Bunches

Empty fruit bunches are among the most frequently examined oil-palm residues in the selected literature. EFB is generated during the processing of fresh fruit bunches at palm-oil mills and represents a concentrated residue stream associated with established processing facilities. Its association with mills provides an important logistical advantage because the resource is generated at identifiable locations rather than being dispersed across large plantation areas.

The selected references investigate EFB in relation to several applications, including thermochemical conversion, biochar production, biofuel and biochemical production, material applications and other forms of valorisation [2, 27, 29, 35, 40, 42]. These applications demonstrate that EFB should not necessarily be considered only as a low-value combustible residue. Depending on its characteristics and the technology adopted, it may serve as a feedstock for energy production or as a precursor for higher-value products.

At the same time, the utilization of EFB requires consideration of moisture, handling and transportation. The economic value of EFB at the conversion facility depends not only on its quantity but also on the cost of moving and preparing the material. Consequently, preprocessing and logistics become important components of any EFB-based energy or biorefinery system.

Oil-Palm Trunks and Fronds

Oil-palm trunks and fronds represent another important category of plantation-derived biomass. Unlike residues generated at processing mills, these materials are distributed throughout plantation areas and are associated with field operations and replanting activities. Their dispersed nature introduces different collection and transportation requirements from those associated with mill residues [4–8, 11–18].

The selected literature considers these materials as potential feedstocks for thermochemical and biochemical conversion and for the production of value-added products. Their lignocellulosic characteristics make them potentially relevant to processes involving pyrolysis, gasification, hydrothermal conversion and other biomass-conversion pathways [26–44].

The utilization of plantation residues also raises questions concerning sustainable resource management. Biomass removal from plantations may interact with existing agricultural practices and soil-management requirements. Therefore, the theoretical availability of trunks and fronds should not automatically be interpreted as the quantity that can be continuously removed for energy purposes. Sustainable biomass assessment requires consideration of existing uses, environmental functions and the long-term management of plantation systems.

Mesocarp Fibre and Palm Kernel Shells

Mesocarp fibre and palm kernel shells are important residues associated with palm-oil milling. Their relatively concentrated generation at processing facilities provides opportunities for integrated energy and material

utilization. The selected literature considers these materials in relation to combustion, gasification, pyrolysis, carbonization and other thermochemical applications [5–8, 26–44].

Palm kernel shells have attracted particular interest as a biomass fuel and as a feedstock for carbon-based products. Their characteristics can make them suitable for thermal conversion, while the resulting carbon-rich products may provide additional routes for valorisation. Similarly, mesocarp fibre can be utilized in energy-generation systems and other conversion processes.

The availability of these residues at processing facilities creates opportunities for integrated biomass systems in which energy and material production can occur near the point of residue generation. Such arrangements can potentially reduce some transportation requirements while allowing existing industrial infrastructure to be incorporated into biomass-energy development.

Palm-Oil Mill Effluent and Wet Biomass

Palm-oil mill effluent represents a different category of biomass resource because it is a liquid organic waste stream rather than a dry lignocellulosic residue. Its composition and high moisture content influence the suitability of different conversion pathways. The selected literature includes biological and biochemical approaches that demonstrate the potential for recovering energy and other products from organic waste streams [9, 45–54].

The utilization of POME illustrates the importance of matching feedstock characteristics with conversion technology. Processes suitable for dry biomass cannot necessarily be applied directly to wet organic residues without additional treatment. Biological conversion pathways, including anaerobic processes, can therefore provide an important route for recovering energy from high-moisture biomass.

From a resource-management perspective, POME also demonstrates how environmental management and energy production can become interconnected. Treatment of organic effluent can potentially be linked with energy recovery, thereby connecting waste management with renewable-energy generation. The resulting system can be viewed as part of a broader circular-economy strategy in which waste streams are treated as resources rather than simply disposal liabilities.

Agricultural and Forestry Residues

Although oil-palm biomass dominates much of the selected literature, Malaysia's biomass resources extend beyond the palm-oil industry. Agricultural and forestry residues provide additional sources of lignocellulosic material that may contribute to a diversified biomass-energy system. The selected references include research on agricultural waste, forest residues, bamboo and other biomass resources [69–77].

The inclusion of these resources is significant because diversification can potentially reduce dependence on a single biomass source. Different agricultural and forestry residues may be available at different locations and times, creating opportunities for complementary supply systems. A conversion facility may therefore be able to utilize multiple feedstocks if the technology is sufficiently flexible.

However, feedstock diversification also increases the complexity of biomass management. Different materials may possess different moisture levels, bulk densities, ash characteristics, chemical compositions and storage requirements. A multi-feedstock facility therefore requires appropriate preprocessing and quality-control systems to maintain stable conversion conditions.

Bamboo as a Potential Biomass Resource

Bamboo represents another lignocellulosic resource addressed in the selected literature. Its characteristics and rapid growth potential make it relevant to discussions of renewable biomass supply and material utilization [69–

73]. Research involving bamboo demonstrates that biomass-energy development does not necessarily need to depend entirely on agricultural residues.

The potential role of bamboo should nevertheless be considered within a broader resource-management framework. Its use for energy may compete with material applications, and its cultivation and harvesting involve land and resource considerations. Consequently, the most appropriate use of bamboo depends on local conditions, existing markets and the relative value of energy and non-energy applications.

The literature therefore supports a broader concept of biomass utilization in which different resources are allocated according to their characteristics and highest-value sustainable applications.

Feedstock Characteristics and Conversion Suitability

Biomass feedstocks differ substantially in their physical and chemical characteristics. These characteristics influence storage, handling, transportation and conversion performance. The selected studies addressing biomass characterization emphasize the importance of understanding feedstock properties when selecting conversion technologies [5–8, 12, 15, 29, 37, 41, 69–77].

Moisture is particularly important because it influences biomass energy density and can affect the efficiency of several thermochemical processes. High-moisture materials may require drying or alternative conversion pathways, while relatively dry materials may be more suitable for direct combustion, gasification or pyrolysis. Similarly, bulk density affects transportation requirements because low-density biomass occupies a large volume relative to its energy content.

Chemical composition is another important consideration. Lignocellulosic biomass generally contains cellulose, hemicellulose and lignin in varying proportions, while ash-forming minerals and other constituents can influence thermal conversion. The characteristics of individual residues therefore influence the products that can be obtained and the operating conditions required.

The selected literature on advanced conversion and biomass characterization indicates that feedstock selection and technology selection should be treated as interconnected decisions rather than separate stages [26–44]. A conversion technology should be matched to the properties of the available biomass, while feedstock preprocessing can be used where appropriate to improve consistency and conversion performance.

Biomass Availability and Spatial Distribution

One of the principal challenges associated with Malaysian biomass resources is their spatial distribution. Agricultural residues may be dispersed over plantation or farming areas, whereas processing residues tend to be concentrated at mills and industrial facilities. This spatial difference has direct implications for supply-chain design.

The selected literature on biomass optimization demonstrates that the location of biomass sources relative to processing facilities can influence the overall feasibility of a project [1, 19–25, 55–63]. A resource that appears abundant at the national level may have limited practical value if it is located far from suitable conversion facilities or requires costly collection and transportation.

Consequently, biomass-resource assessment should ideally include geographic information and spatial analysis. Facility-location models and transportation optimization can help determine where conversion plants should be located and how biomass should be allocated among competing facilities. These approaches can transform resource assessments from simple estimates of biomass quantities into more practical assessments of recoverable and economically accessible feedstock.

Competing Uses and Sustainable Biomass Allocation

Biomass resources may have multiple potential uses. Agricultural residues can be used for energy, soil management, animal-related applications, material production or industrial processing. Oil-palm residues may also be used internally within mills or sold to external users. The allocation of biomass to energy production must therefore be considered in relation to these competing uses [1, 11, 19, 24, 64–68].

This issue is particularly important when assessing the concept of biomass "potential." The theoretical potential represents the total resource generated, whereas the technically available potential accounts for the characteristics of the feedstock and collection technology. The economically available potential additionally considers costs and market conditions, while the sustainably available potential must account for environmental constraints and competing uses.

The selected literature supports the need for this distinction. Biomass-energy planning based solely on gross residue generation may overestimate the amount of material that can actually be mobilized. A more realistic assessment requires consideration of the complete biomass value chain, from generation through collection, transportation and conversion.

Biomass Characterization, Preprocessing and Quality Control

Preprocessing represents an important intermediate stage between biomass collection and conversion. Depending on the feedstock, preprocessing may involve drying, size reduction, densification, separation or other treatments intended to improve handling and conversion characteristics.

The importance of preprocessing arises from the variability of biomass. Feedstocks collected from different locations or at different times may have different moisture levels, particle sizes and compositions. Without adequate quality control, this variability can affect the stability of conversion systems.

The selected literature on thermochemical processing and biomass upgrading includes approaches such as torrefaction and other preprocessing technologies that can modify biomass properties [36–44]. These approaches demonstrate that preprocessing can serve not merely as a logistical operation but also as a method of improving fuel quality and enabling more efficient integration with downstream conversion systems.

Biomass Resource Traceability and Digital Management

The increasing complexity of biomass supply chains creates a need for improved information management. Digital traceability can potentially provide information concerning the origin, quantity, quality, movement and utilization of biomass resources. The selected literature addressing digitalization, Industry 4.0 and related approaches indicates growing interest in applying digital technologies to biomass management [61, 66, 71, 96]. Traceability may become particularly important where biomass-derived products must demonstrate information concerning feedstock origin or sustainability characteristics. Digital monitoring can also support inventory management, transportation planning and quality assurance.

The integration of digital technologies with biomass supply chains therefore represents a potential development pathway for Malaysia. However, the effectiveness of such systems depends on data availability, interoperability, infrastructure and participation across the supply chain.

Resource Potential for Integrated Biomass Systems

The diversity of Malaysian biomass resources creates opportunities for integrated systems in which several feedstocks and conversion technologies operate within a coordinated framework. Instead of relying on one residue and one conversion process, an integrated biomass facility could potentially utilize different feedstocks according to seasonal availability and process requirements.

Such integration may improve resource utilization by directing different fractions towards different applications. For example, relatively dry lignocellulosic materials may be suitable for thermochemical conversion, while wet organic residues may be directed towards biological processes. Other fractions may be more appropriate for material or chemical applications.

The selected literature on biomass valorisation, biorefinery systems and circular-economy applications supports the concept of cascading resource use [2, 26–35, 42, 45, 88–94]. Under this approach, biomass is allocated according to its potential value, with energy recovery forming one component of a wider resource-utilization strategy.

Challenges Associated with Biomass Feedstock Development

Despite the substantial resource base, several challenges influence the practical development of biomass energy in Malaysia. These include feedstock heterogeneity, geographical dispersion, transportation requirements, storage, seasonal variations, competing uses and the cost of collection and preprocessing [1, 19–25, 55–63].

Another challenge concerns the establishment of reliable long-term feedstock supply arrangements. Commercial conversion facilities require a reasonably consistent supply of suitable material. Variability in biomass generation or changes in competing markets can create uncertainty for facility operation and investment.

The development of standardized biomass specifications may therefore be important. Consistent quality standards can facilitate trading, improve technology compatibility and support more reliable economic assessments. Digital traceability and improved supply-chain coordination may complement such standards by providing information on feedstock origin and quality.

From Biomass Availability to Sustainable Feedstock Supply

The selected literature demonstrates that the concept of biomass availability should be interpreted as a continuum rather than a single quantity. At the beginning of the chain is the total biomass generated by agricultural, forestry and industrial activities. A proportion of this material may be technically recoverable, while a smaller proportion may be economically accessible. After accounting for competing uses and environmental constraints, the sustainably available quantity may be smaller still.

This distinction is important for Malaysian biomass-energy planning because investment decisions depend on reliable feedstock rather than theoretical resource estimates. Conversion facilities require predictable supplies over their operating lifetimes, and therefore long-term feedstock availability must be considered alongside current resource estimates.

The development of biomass energy consequently requires closer integration between resource assessment, logistics planning and technology selection. A biomass resource becomes commercially meaningful only when it can be consistently collected, transported, processed and converted at an acceptable cost and within appropriate environmental constraints.

SUMMARY

Malaysia's biomass resource base provides a diverse foundation for renewable-energy and biomass-valorisation development. Oil-palm residues constitute a major component of this resource base, encompassing EFB, trunks, fronds, fibres, palm kernel shells and POME, while agricultural residues, forestry resources, bamboo and other lignocellulosic materials provide opportunities for diversification [1–18, 69–77].

The selected literature demonstrates that the potential of these resources is determined not solely by their quantity but by their physical and chemical characteristics, geographical distribution, competing uses, collection

requirements and compatibility with available conversion technologies. Moisture, bulk density, composition, storage characteristics and quality variability can influence the technical and economic performance of downstream processes.

A central implication is that biomass-resource assessment should move beyond simple estimates of residue generation. Sustainable biomass development requires an understanding of how resources can be recovered, transported, preprocessed and allocated among energy, material and chemical applications. Supply-chain optimization, digital traceability and improved resource characterization can contribute to this process, while integrated and cascading utilization can potentially increase the value obtained from each biomass stream.
Accordingly, biomass resources in Malaysia should be viewed as components of a broader interconnected value chain. The characteristics and location of each feedstock influence the selection of conversion technology, while the choice of technology affects logistics, economics, environmental performance and the range of products that can be produced. This relationship provides the basis for the next section, which examines the principal conversion and valorisation technologies applicable to Malaysian biomass.

Conversion And Valorisation Technologies

Overview of Biomass Conversion Pathways

The diversity of biomass resources available in Malaysia is accompanied by a similarly diverse range of conversion and valorisation technologies. The selected literature demonstrates that Malaysian biomass has been investigated through thermochemical, biological and biochemical pathways, with applications extending from direct heat and electricity generation to gaseous fuels, liquid fuels, chemicals, biochar and advanced carbon-based products [2, 9, 26–54]. The choice of conversion pathway is strongly related to feedstock characteristics, particularly moisture content, chemical composition, physical form and availability.

Biomass conversion should therefore not be considered as a single technological category. Different pathways transform biomass into different combinations of products and require different feedstock conditions and supporting infrastructure. Conventional combustion may be appropriate where the primary objective is heat or electricity generation, whereas gasification can produce synthesis gas that provides a route towards energy or chemical applications. Pyrolysis can generate bio-oil, gases and solid carbonaceous products, while torrefaction can modify biomass properties before subsequent utilization. Biological and biochemical pathways provide additional options for wet organic residues and for the production of fuels and chemicals [26–54].

The selected literature further indicates a movement from simple energy recovery towards biomass valorisation. Under a valorisation approach, biomass is considered a source of multiple products rather than merely a combustible material. This perspective is particularly relevant to Malaysia because the country's biomass streams can potentially support integrated biorefinery systems in which energy production is combined with the production of chemicals, fuels, materials and other value-added products [2, 27, 35, 42, 45, 88–94].

Direct Combustion and Energy Recovery

Combustion is one of the most established methods of converting biomass into useful energy. In a biomass combustion system, the organic material is oxidized to generate heat, which can subsequently be used directly or converted into electricity through appropriate energy-conversion equipment.

The selected literature on oil-palm residues and other agricultural biomass demonstrates the relevance of thermochemical energy recovery within Malaysia [5–8, 26–30]. Residues generated by palm-oil processing can provide relatively concentrated sources of combustible material, creating opportunities for integration with existing industrial energy requirements.

One important advantage of direct combustion is its relatively straightforward relationship between biomass feedstock and useful energy. However, the performance of combustion systems depends on feedstock characteristics. Moisture content, ash content, particle size and chemical composition can affect combustion

behavior and system performance. Consequently, feedstock preparation and quality control remain important even for relatively conventional conversion systems.

Combustion is also influenced by the scale of the facility. Where biomass is generated at industrial sites, on-site energy recovery may reduce some transportation requirements and allow energy to be used directly within the facility. Larger centralized systems, in contrast, may require more extensive collection and transportation networks. The economic and environmental performance of combustion therefore depends on the relationship between the biomass source, facility location and energy demand.

Biomass Co-Firing

Co-firing represents an approach in which biomass is utilized alongside another fuel within an existing or modified energy-generation system. The selected literature includes work relevant to biomass utilization in energy systems and the integration of biomass with broader energy infrastructure [26–32].

The potential significance of co-firing lies in its ability to connect biomass resources with existing energy infrastructure rather than requiring an entirely independent energy system. Biomass residues may therefore serve as supplementary renewable inputs within systems originally designed around conventional fuels.

However, co-firing also requires attention to biomass quality, fuel preparation, supply reliability and compatibility with existing equipment. Variations in moisture, ash characteristics and fuel composition can influence operational requirements. Consistent feedstock supply is consequently important for maintaining reliable operation.

For Malaysia, co-firing can be considered within a broader strategy for incorporating biomass into an increasingly diversified energy system. Its potential role depends on the availability of suitable biomass, infrastructure compatibility, economic conditions and the policy environment governing renewable-energy deployment.

Gasification

Gasification is another major thermochemical pathway identified in the selected literature. Rather than converting biomass directly through complete combustion, gasification produces a combustible synthesis gas under controlled conditions. The resulting gas can potentially be used for energy generation or as an intermediate for further chemical processing.

The selected references include research on gasification and the utilization of synthesis gas generated from agricultural waste [3, 26, 31–38]. These studies illustrate the potential for converting low-value agricultural residues into gaseous energy carriers.

Gasification can be particularly relevant where the objective extends beyond direct heat generation. Synthesis gas may provide flexibility in downstream applications, although the feasibility of such systems depends on gas quality, cleaning requirements, process integration and the intended end use.

Feedstock preparation is also important for gasification. Biomass variability can affect gasification performance, while moisture and particle characteristics can influence process requirements. The supply-chain system must therefore deliver feedstock within specifications suitable for stable operation.

Pyrolysis

Pyrolysis involves the thermal decomposition of biomass under conditions with limited oxygen availability. Depending on process conditions and feedstock characteristics, the process can produce liquid, gaseous and solid products. The selected literature investigates pyrolysis of oil-palm and other lignocellulosic residues for energy and value-added applications [27–44]. One of the principal attractions of pyrolysis is its ability to produce several product streams from a single biomass feedstock. Bio-oil can potentially be further processed into fuels or chemicals, gases can be used for energy recovery, and the solid fraction can be utilized as a carbon-rich product.

The possibility of producing multiple outputs makes pyrolysis particularly relevant to the concept of biomass valorisation. Instead of viewing biomass solely as a fuel, pyrolysis allows different fractions of the feedstock to be directed towards different applications.

However, the technical and economic performance of pyrolysis depends on process conditions, feedstock characteristics, product quality and downstream processing requirements. Bio-oil, in particular, may require upgrading before use in applications where fuel or chemical specifications are stringent. Consequently, the conversion process should be considered as part of a larger value chain rather than as an isolated reactor operation.

Bio-Oil and Its Upgrading

Bio-oil is one of the products associated with biomass pyrolysis and has been investigated as a potential intermediate for energy and chemical applications. The selected literature includes studies concerning pyrolysis products and the upgrading or utilization of biomass-derived oils [35–44].

The development of bio-oil pathways is relevant to Malaysia because locally available agricultural residues can provide renewable carbon feedstocks. However, the value of bio-oil depends on its properties and the market into which it is introduced. Additional processing may be required to improve characteristics relevant to storage, handling, combustion or chemical conversion.

Consequently, bio-oil production should be assessed together with downstream upgrading and market requirements. A technically successful pyrolysis process may not automatically represent a commercially viable system if the resulting oil has limited market value or requires extensive upgrading.

The selected literature therefore supports the broader principle that conversion technologies should be evaluated across the complete product chain. Feedstock preparation, conversion, product recovery, upgrading and final utilization all contribute to the overall performance of a biomass system.

Torrefaction

Torrefaction is a thermochemical preprocessing approach that modifies the characteristics of biomass through controlled heating. The selected literature includes research on biomass upgrading and thermochemical treatment, particularly in relation to improving the handling and fuel characteristics of lignocellulosic materials [36–44].

The importance of torrefaction arises from the challenges associated with transporting and storing low-density and moisture-sensitive biomass. Modification of biomass properties can potentially improve its suitability for storage, transportation and subsequent energy conversion.

For Malaysia, torrefaction may be particularly relevant where biomass resources must be transported over significant distances. By improving the physical characteristics of the material, preprocessing may alter the economics of biomass logistics.

However, torrefaction itself consumes energy and requires additional equipment. Its overall value therefore depends on whether the improvements in handling and conversion performance compensate for the additional processing requirements. This illustrates the broader need to evaluate preprocessing as part of the complete biomass supply chain.

Hydrothermal Carbonization

Hydrothermal carbonization provides another thermochemical pathway for biomass conversion and is particularly relevant to biomass streams containing significant moisture. The selected literature includes work examining hydrothermal approaches and the production of carbon-rich materials from biomass [39–44].

An important feature of hydrothermal processing is that it can reduce the dependence on conventional drying for certain wet feedstocks. This characteristic may provide opportunities for utilizing biomass resources that are less suitable for dry thermochemical processes.

The resulting carbon-rich products may have applications in energy, soil-related uses or other material pathways depending on their characteristics. Consequently, hydrothermal processing can be viewed not simply as an energy-conversion technology but as a potential route for biomass carbon valorisation.

As with other emerging technologies, however, commercialization requires consideration of capital requirements, process integration, product markets and environmental performance.

Biogas and Anaerobic Conversion

Biological conversion represents an important alternative to thermochemical processing, particularly for wet organic biomass. Anaerobic processes can convert suitable organic material into biogas, which can subsequently be used as an energy carrier.

The selected literature includes research on biogas and biological utilization of organic residues [9, 45–54]. These studies are particularly relevant to waste streams such as POME and other organic residues where high moisture content can make conventional thermochemical processing less attractive.

Biogas systems can also support the integration of waste treatment and energy recovery. Instead of treating organic residues solely as waste requiring disposal, anaerobic conversion can recover energy while simultaneously contributing to waste-management objectives.

The broader significance of biogas therefore extends beyond energy production. It provides an example of how biomass conversion can contribute simultaneously to resource recovery, environmental management and renewable-energy generation.

Biofuels and Biochemical Conversion

The selected references also investigate the conversion of biomass into liquid fuels and biochemical products, including bioethanol, biobutanol and bio-succinic acid [2, 45–54]. These pathways broaden the role of biomass beyond electricity and heat generation.

Biochemical conversion is particularly significant because lignocellulosic biomass contains structural carbohydrates that can potentially be converted into intermediate sugars and subsequently into fuels or chemicals. Such processes provide opportunities for developing biorefinery systems in which a single biomass resource supports multiple product streams.

The zero-waste conversion of oil-palm biomass into bio-succinic acid, for example, illustrates the possibility of using agricultural residues as feedstocks for higher-value chemical production [2]. Such applications can alter the economic rationale for biomass utilization because the value of the final product may exceed that obtainable through direct combustion.

Nevertheless, biochemical pathways can involve more complex processing chains than direct energy recovery. Pretreatment, hydrolysis, fermentation, separation and purification may all be required depending on the product. Their feasibility must therefore be assessed alongside technological maturity, capital requirements and market demand.

Integrated Biorefinery Approaches

The concept of a biorefinery provides a framework for combining several biomass conversion pathways within a coordinated system. Rather than directing an entire feedstock toward a single product, a biorefinery separates or transforms biomass into multiple streams that can be utilized for energy, fuels, chemicals and materials.

The selected literature supports this concept through research on zero-waste conversion, biofuels, biochemical products, pyrolysis, biochar and advanced biomass-derived materials [2, 27, 35, 42, 45, 49, 88–94].

For Malaysia, integrated biorefineries may be particularly relevant to oil-palm processing because several biomass streams are already concentrated at palm-oil mills. A single industrial location may therefore provide access to multiple feedstocks that can be allocated to different conversion pathways.

Such integration can potentially improve resource efficiency by reducing the quantity of material requiring disposal and by increasing the range of products generated. It may also provide opportunities for internal energy integration, in which one process supplies energy or intermediate products required by another.

However, integrated systems are also more complex than single-product facilities. They require coordinated process design, reliable feedstock supply, multiple product markets and potentially greater capital investment. Their successful development therefore depends on integration across technical, economic and institutional dimensions.

Biochar and Carbon-Rich Products

Biochar is another important biomass-derived product identified in the selected literature. It can be produced through thermochemical processes such as pyrolysis and related carbonization pathways [35, 40–44, 88–94].

The significance of biochar lies in its ability to provide a non-energy application for biomass carbon. Depending on its properties and intended application, biochar may be considered for soil-related uses, environmental applications or other material pathways.

From a biomass-valorisation perspective, biochar illustrates the potential to generate products that do not depend exclusively on conventional energy markets. This diversification may be relevant when electricity or fuel markets alone do not provide sufficient value to justify biomass conversion.

The environmental implications of biochar systems nevertheless depend on feedstock origin, production conditions, transportation, application and the treatment of carbon within the overall system boundary. Consequently, biochar pathways should be assessed using appropriate life-cycle and sustainability frameworks.

Advanced Biomass-Derived Materials

The selected references extend biomass utilization into the production of advanced materials and carbon-based products [88–94]. This represents an important shift from the traditional waste-to-energy model towards higher-value resource utilization.

Oil-palm residues and other lignocellulosic materials contain carbon and structural components that can potentially serve as precursors for materials with specialized properties. Such applications may provide additional value from biomass that would otherwise have relatively low economic value.

The development of advanced materials also highlights the importance of cascading biomass use. Where a biomass fraction can be converted into a high-value material, direct combustion may not necessarily represent the only or highest-value utilization pathway. Energy recovery can instead be considered for residual fractions that remain after higher-value components have been extracted.

Feedstock–Technology Matching

The selected literature demonstrates that technology selection must be closely matched to feedstock characteristics. Dry lignocellulosic materials may be suitable for combustion, gasification, pyrolysis or torrefaction, while high-moisture organic residues may be more appropriate for biological conversion or hydrothermal processing [26–54].

This relationship is central to the design of Malaysian biomass systems. A technology should not be selected solely because it has demonstrated high performance under laboratory or pilot conditions. Its suitability must also be evaluated in relation to the characteristics and availability of the biomass that can actually be supplied.

Feedstock–technology matching also affects economic performance. If extensive preprocessing is required to make a feedstock suitable for a particular process, the additional cost may alter the viability of the project. Conversely, selecting a technology that is inherently compatible with the available feedstock may reduce preprocessing requirements.

Technology Scale and Integration with Existing Infrastructure

The scale of a biomass conversion facility is another important consideration. Small distributed facilities may reduce transportation distances because processing occurs close to biomass sources. Larger centralized facilities may benefit from economies of scale but require greater quantities of feedstock and potentially longer transportation networks.

The selected literature on biomass supply-chain optimization and facility planning demonstrates the importance of considering technology scale together with feedstock distribution [1, 19–25, 55–63].

Existing industrial infrastructure may also provide opportunities for integration. Palm-oil mills, for example, already represent important points of biomass concentration. Converting residues near these facilities could potentially reduce certain logistics requirements and allow existing energy, water and processing infrastructure to be utilized.

The appropriate scale is therefore not simply a technical decision. It represents a trade-off among economies of scale, transportation costs, feedstock availability, product markets and infrastructure.

Conversion Efficiency and Overall System Performance

Conversion efficiency is an important technical consideration, but the selected literature suggests that it should not be considered in isolation. A technology with high conversion efficiency may still face economic or logistical constraints if feedstock collection is expensive or product markets are limited.

Similarly, a pathway producing several products may have a lower direct energy-conversion efficiency while generating greater overall value through co-products. This is particularly relevant to biorefineries and integrated valorisation systems.

A comprehensive assessment should therefore consider multiple indicators, including feedstock utilization, energy recovery, product yield, capital and operating requirements, emissions, logistics and market value. Such a systems perspective is necessary to compare fundamentally different biomass pathways without reducing the analysis to a single technical parameter.

Circular-Economy Implications of Biomass Conversion

The conversion technologies identified in the selected literature have broader implications for circular-economy development. Agricultural and industrial residues can be transformed into energy, fuels, chemicals and materials, thereby reducing reliance on disposal-oriented approaches [2, 26–35, 42, 45, 88–94].

The circular-economy perspective also encourages cascading use. Biomass may first be directed toward material or chemical applications, followed by energy recovery from residual fractions. This approach can potentially retain greater economic value within the biomass resource.

For Malaysia, such a strategy could link biomass-energy development with industrial diversification. Agricultural residues would become inputs into interconnected value chains rather than isolated waste streams.

This could support the development of new processing industries while simultaneously contributing to renewable-energy objectives.

Environmental Considerations of Conversion Technologies

Each conversion pathway presents environmental considerations that need to be assessed within its complete life cycle. Thermochemical systems involve energy use and emissions associated with conversion, while biological systems require appropriate management of residues and process inputs.

The selected literature on life-cycle assessment emphasizes the importance of considering the entire system rather than only the conversion stage [78–84, 100]. Feedstock collection, transportation, preprocessing, conversion, product use and co-product treatment can all influence environmental performance.

This is particularly important when comparing biomass pathways with other renewable-energy technologies. A biomass system may provide renewable energy while also requiring significant logistics and processing infrastructure. Environmental assessment must therefore consider the complete supply chain and establish appropriate system boundaries.

Technology Development Challenges

Despite the wide range of conversion technologies investigated in the selected literature, several challenges remain relevant to large-scale deployment. These include feedstock variability, process complexity, capital requirements, product quality, technology integration and market development [26–54, 85–94].

Emerging technologies may require further demonstration at commercial scale, while established technologies may face challenges associated with feedstock logistics and economic competitiveness. The development of integrated systems can also introduce additional operational complexity.

The commercialization pathway therefore requires more than technological innovation. It requires coordinated development of reliable feedstock systems, infrastructure, financing mechanisms, standards, markets and policy support.

Future Direction: From Energy Recovery to Biomass Valorisation

The selected literature indicates a gradual transition from the concept of biomass as a source of renewable energy towards a broader concept of biomass as a renewable carbon resource. This transition is reflected in research on biofuels, biochemicals, biochar, advanced materials, biorefineries and integrated conversion systems [2, 27, 35, 42, 45, 88–94].

For Malaysia, this development is particularly relevant because the country's biomass resources are diverse and closely connected to established agricultural and industrial activities. Future biomass systems may therefore combine several technologies rather than relying on a single conversion route.

Such systems could integrate thermochemical and biological processes, utilize multiple feedstocks and produce combinations of energy and higher-value products. The appropriate configuration will depend on local resource characteristics, market demand, infrastructure and environmental constraints.

SUMMARY

The selected literature demonstrates that Malaysia possesses a broad technological portfolio for converting biomass into energy and value-added products. Combustion and co-firing provide routes for direct energy recovery, while gasification offers synthesis-gas production and potential integration with energy and chemical applications. Pyrolysis provides multiple product streams, including bio-oil, gases and carbon-rich solids, while torrefaction and hydrothermal processes provide additional approaches to biomass upgrading and conversion [26–44].

Biological and biochemical pathways provide complementary opportunities, particularly for wet organic residues and the production of biogas, biofuels and biochemical products [45–54]. At the same time, research on biochar, advanced materials and biorefinery systems demonstrates the increasing importance of biomass valorisation beyond conventional energy production [2, 35, 88–94].

The central finding from this body of literature is that conversion technology cannot be separated from feedstock characteristics, logistics, economics and product markets. The most appropriate pathway depends on the type and quality of biomass available, the scale and location of the facility, the desired products and the surrounding infrastructure. Consequently, the development of Malaysian biomass energy requires an integrated approach in which energy generation is considered alongside material and chemical valorisation.

The next section examines the supply-chain, logistics and system-optimization challenges that determine whether these conversion technologies can obtain reliable and economically accessible biomass feedstocks.

Supply Chain, Logistics And System Optimization

Introduction

The availability of biomass resources does not automatically translate into a reliable supply of feedstock for energy and conversion facilities. Biomass is fundamentally different from conventional energy commodities because it is often geographically dispersed, bulky, heterogeneous and generated as a secondary output of agricultural, plantation, forestry and industrial activities. Consequently, the collection, transportation, storage, preprocessing and allocation of biomass can represent major components of the overall system.

The selected literature emphasizes the importance of supply-chain management in determining the feasibility of biomass-energy systems in Malaysia [1, 19–25, 55–63]. Research in this area includes mathematical optimization, facility-location models, routing approaches, simulation, genetic algorithms, system modelling and digital technologies. These approaches reflect the need to coordinate multiple actors and physical flows between biomass sources and conversion facilities.

The supply chain can therefore be viewed as a critical connection between the resource potential discussed in Section 2 and the conversion technologies discussed in Section 3. A technically appropriate conversion technology cannot operate effectively without an adequate and reliable supply of suitable biomass. Similarly, a large biomass resource base may have limited commercial value if the cost of recovering and transporting the material is excessive.

Structure of the Malaysian Biomass Supply Chain

A biomass supply chain generally begins with biomass generation at agricultural fields, plantations, mills, forestry operations or other industrial sources. The material then moves through one or more stages of collection, aggregation, transportation, storage and preprocessing before reaching a conversion facility. Following conversion, energy, fuels, chemicals or other products are delivered to markets or end users.

For Malaysia, the structure of this chain varies considerably according to feedstock type. Oil-palm trunks and fronds are primarily associated with plantation areas, while EFB, mesocarp fibre and palm kernel shells are concentrated at palm-oil processing facilities. POME is generated at mills as a wet organic residue. Agricultural and forestry residues may be distributed across much wider geographic areas [1–18, 69–77].

These differences mean that a single logistics model cannot necessarily be applied to all biomass resources. The appropriate supply-chain structure depends on the location and physical characteristics of the feedstock, the location of the conversion facility and the characteristics of the final product.

Biomass Collection

Collection represents the first major logistical challenge in biomass utilization. Agricultural and plantation residues can be dispersed over large areas, requiring equipment, labour and transportation resources to aggregate sufficient quantities for processing.

The selected literature indicates that collection strategies must consider both the quantity and physical characteristics of biomass [1, 19–25]. A collection system that is suitable for one residue may not be suitable for another because of differences in bulk density, moisture, accessibility and generation patterns.

Collection also affects the sustainability of biomass systems. Removing excessive quantities of agricultural residues may interfere with existing land-management practices or competing uses. Therefore, the objective is not simply to maximize collection but to identify an appropriate quantity that can be recovered consistently while maintaining environmental and economic constraints.

Transportation and Distance

Transportation is one of the most important factors influencing biomass supply-chain economics. Biomass generally has a lower bulk energy density than conventional fossil fuels, and some residues contain substantial quantities of water. Moving large quantities over long distances can therefore increase fuel consumption, operating costs and environmental burdens.

The selected references examining biomass logistics and optimization demonstrate the importance of transportation distance and route selection [1, 19–25, 55–63]. The location of a conversion facility relative to biomass sources can significantly influence the amount of material that can be economically supplied.

This relationship creates an important spatial consideration for biomass development. Instead of asking only how much biomass exists within a country or region, planners must determine where the biomass is located and how far it must travel to reach an appropriate conversion facility.

Facility Location

Facility location is closely connected to transportation and feedstock availability. A conversion plant located too far from biomass sources may face high logistics costs, while a facility located close to one resource cluster may have difficulty obtaining sufficient quantities when supply conditions change.

The selected literature includes mathematical optimization approaches for determining suitable facility locations and biomass allocations [1, 19–25, 55–63]. Such approaches can incorporate variables including feedstock availability, transportation distance, plant capacity, operating costs and market demand.

The location decision is therefore a strategic component of biomass-energy planning. It can determine the radius from which feedstock must be collected and the transportation infrastructure required to maintain plant operation.

Mixed-Integer Linear Programming and Optimization

One of the approaches identified in the selected literature is mixed-integer linear programming (MILP). MILP models can represent discrete decisions such as whether to construct a facility, which sources should supply a facility and how biomass should be allocated across a network [1].

The application of MILP to biomass management demonstrates how mathematical optimization can support decisions involving multiple interacting constraints. These models can be used to examine different facility configurations and resource-allocation strategies.

For Malaysian biomass systems, optimization models are particularly relevant because resources are dispersed and may have multiple competing uses. A model can potentially identify combinations of facility locations, transportation routes and feedstock allocations that satisfy operational requirements while considering economic or environmental constraints.

However, optimization results depend on the assumptions and data incorporated into the model. The quality of biomass-resource estimates, transportation costs, facility capacities and demand assumptions therefore affects the reliability of planning outcomes.

Location-Routing and Network Optimization

Biomass supply chains can also be analyzed through location-routing approaches that simultaneously consider where facilities should be established and how biomass should be transported between sources and facilities.

The selected literature includes studies addressing logistics and network optimization using different mathematical and computational techniques [19–25, 55–63]. These approaches recognize that facility location and transportation decisions are interconnected.

For example, locating a facility closer to one group of biomass sources may reduce transportation requirements for those sources while increasing the distance for others. A network-level model can examine these trade-offs rather than treating facility location and transportation as independent decisions.

Such approaches can be particularly useful for regional biomass hubs where material from multiple farms, plantations or processing facilities is aggregated before being sent to a conversion plant.

Biomass Hubs and Aggregation

The concept of biomass aggregation provides a potential solution to the dispersed nature of biomass resources. Instead of transporting small quantities directly from individual sources to large conversion plants, biomass can be collected at intermediate hubs where it is sorted, stored, dried, densified or otherwise prepared.

Aggregation can improve the efficiency of downstream transportation by creating larger and more consistent loads. It can also provide a location where biomass quality can be assessed before conversion.

For Malaysia, biomass hubs may be relevant in areas where agricultural or plantation residues are widely dispersed. They could provide a link between rural biomass producers and larger industrial conversion facilities. However, establishing hubs introduces additional infrastructure and operating requirements. Their feasibility therefore depends on sufficient biomass density and the ability of the resulting logistics improvements to justify the additional costs.

Storage and Seasonal Availability

Storage is another important component of biomass supply chains. Biomass generation may vary according to harvesting cycles, agricultural seasons, weather conditions and industrial production patterns. Conversion facilities, however, may require relatively continuous feedstock supplies.

The selected literature's emphasis on supply-chain optimization implies the importance of coordinating biomass availability with plant demand [1, 19–25, 55–63]. Storage can provide a mechanism for balancing variations between supply and demand.
At the same time, biomass storage can introduce technical challenges. Moisture changes, biological degradation and changes in material quality may affect stored biomass. Appropriate storage systems must therefore be matched to the characteristics of the feedstock.

Storage requirements also have economic implications because additional land, infrastructure and handling equipment may be required. The optimal storage strategy therefore depends on the characteristics of the resource and the operational requirements of the conversion facility.

Preprocessing and Densification

Preprocessing can improve the physical properties of biomass before transportation or conversion. Depending on the feedstock, preprocessing may include drying, grinding, size reduction, densification or thermochemical upgrading.

The selected literature on torrefaction and other biomass-upgrading technologies demonstrates that preprocessing can change the energy density and handling characteristics of biomass [36–44]. This can influence both transportation efficiency and conversion performance.

Densification can be particularly useful for low-density biomass because increasing bulk density can allow more material to be transported within a given vehicle capacity. However, densification itself requires energy and equipment. The overall benefit therefore depends on the balance between preprocessing costs and logistics savings.

Supply-Chain Reliability

A commercial biomass facility requires more than a large theoretical resource. It requires a reliable and predictable feedstock supply. Variability in biomass availability can affect plant utilization and therefore the economic performance of the facility.

The selected literature on biomass optimization emphasizes the need to account for resource availability and operational constraints [1, 19–25]. Supply reliability is influenced by agricultural production, seasonal variations, competing users and transportation disruptions.

Long-term supply arrangements can potentially reduce uncertainty by establishing predictable relationships between biomass producers and conversion facilities. However, the appropriate contractual structure depends on local market conditions and the characteristics of the biomass resource.

Multi-Feedstock Supply Systems

The diversity of Malaysian biomass resources creates the possibility of multi-feedstock conversion systems. A facility may potentially use more than one biomass type to maintain feedstock availability and improve plant utilization.

Multi-feedstock systems can provide flexibility when individual resources are seasonal or geographically concentrated. For example, different agricultural residues could potentially complement one another over different periods of the year.

However, using multiple feedstocks also increases operational complexity. Different materials may require different preprocessing conditions and may behave differently during conversion. Feedstock blending therefore requires appropriate characterization and quality-control systems.

Supply-Chain Optimization Under Uncertainty

Biomass supply chains are inherently uncertain. The actual quantity of recoverable biomass can differ from estimates because of weather, agricultural production, market conditions, competing uses and operational constraints.

Optimization models can incorporate some of these uncertainties through scenarios or alternative assumptions. The selected literature demonstrates the increasing use of computational approaches to improve biomass-system planning [1, 19–25, 55–63].

For future Malaysian biomass development, uncertainty-aware planning is particularly important because investment decisions often involve long operating periods. A facility designed around a single fixed estimate of biomass availability may be vulnerable if actual supply conditions differ significantly.

Environmental Considerations in Biomass Logistics

Transportation and preprocessing contribute to the environmental footprint of biomass systems. Although biomass itself is renewable, the movement of feedstocks can involve fuel consumption and associated emissions. The selected life-cycle literature indicates that these upstream stages need to be incorporated into environmental assessment [78–84, 100]. A biomass conversion technology may have favorable environmental characteristics at the processing stage while its overall performance is affected by long transportation distances or energy-intensive preprocessing.

This reinforces the importance of locating facilities appropriately and optimizing transportation networks. Reducing unnecessary movement of biomass can potentially improve both economic and environmental performance.

Digitalization of Biomass Supply Chains

Digital technologies provide opportunities to improve the coordination and visibility of biomass supply chains. The selected references include research related to digitalization, Industry 4.0 and traceability [61, 66, 71, 96]. Digital systems can potentially record biomass quantities, source locations, quality characteristics and transportation status. This information could be used to improve inventory management, route planning and feedstock allocation.

Real-time information may also allow conversion facilities to respond to changes in biomass availability. For example, if one supply source experiences a temporary reduction, alternative sources may be identified and incorporated into the supply network.

Digitalization may therefore become an enabling infrastructure for large-scale biomass deployment, particularly where supply chains involve numerous producers and geographically dispersed resources.

Traceability and Sustainability Verification

Traceability is increasingly relevant when biomass-derived products need to demonstrate information about their origin and sustainability characteristics. Digital tracking systems can potentially link biomass feedstocks to their sources and document their movement through the supply chain.

The selected literature addressing traceability and digital management indicates that information systems can support more transparent biomass value chains [61, 66, 71, 96].

For Malaysia, traceability could be relevant to both domestic and international markets. Products derived from biomass may increasingly need to demonstrate environmental or sustainability characteristics depending on market requirements and regulatory frameworks.
The development of reliable traceability systems would therefore require coordination among producers, transport operators, processors, conversion facilities and product markets.

Biomass Supply Chains and Rural Development

Biomass supply chains can connect rural resource producers with industrial energy and processing markets. Collection, transportation, preprocessing and aggregation activities can create opportunities for local businesses and employment.

The selected literature's broader economic and sustainability themes suggest that biomass development should not be evaluated only according to the performance of the central conversion facility [64–68, 85–91]. The wider supply chain may generate additional economic activity.

However, the distribution of benefits depends on the organization of the supply chain. The participation of small producers, local businesses and rural communities can be influenced by procurement arrangements, infrastructure and market access.

Optimization Across Competing Biomass Uses

One of the most important challenges in biomass management is deciding how available resources should be allocated among competing uses. Biomass may be directed towards electricity, heat, biofuels, chemicals, materials, biochar or other applications.

The selected literature on biomass management and valorisation supports the use of optimization approaches to evaluate alternative allocation strategies [1, 19–25, 64–68]. The objective should not necessarily be to maximize the quantity of biomass converted into energy, but rather to identify resource allocations that are consistent with economic, environmental and sustainability objectives.

This perspective is particularly important where higher-value material or chemical applications compete with energy production. A cascading strategy may allocate the most suitable fractions to high-value products and use remaining material for energy recovery.

Integration of Supply Chain and Conversion Technology

Supply-chain design and conversion-technology selection should be treated as interconnected decisions. A technology requiring highly consistent feedstock may require a more sophisticated preprocessing and aggregation system than a technology capable of handling heterogeneous biomass.

Conversely, a technology that can operate close to biomass sources may reduce transportation requirements and enable the use of resources that would otherwise be uneconomic to transport.

The selected literature therefore supports an integrated planning approach in which feedstock characteristics, technology selection, plant capacity and logistics are evaluated simultaneously [1, 19–25, 26–63].

Biomass Supply Chains in an Integrated Energy System

Biomass can also form part of a diversified energy system that includes solar energy, storage and other renewable technologies. The selected literature concerning energy transition and comparative renewable-energy assessment demonstrates the importance of considering biomass within the broader energy system rather than as an isolated technology [80, 100].

Biomass can potentially provide dispatchable renewable energy, while variable renewable technologies can contribute electricity under appropriate resource conditions. The resulting combination may support a more diversified energy architecture.

However, the appropriate role of biomass depends on the specific energy system, resource availability and environmental objectives. Integration should therefore be assessed using system-level economic and environmental analysis.

Supply-Chain Challenges for Commercial Deployment

Several challenges remain important for the commercialization of Malaysian biomass systems. These include:

- Geographically dispersed biomass resources;
- High transportation requirements for bulky materials;
- Variability in feedstock quality and availability;

- Seasonal resource generation;
- Storage requirements;
- Competition among biomass users;
- Limited or inconsistent supply information;
- Preprocessing costs;
- Infrastructure requirements; and
- Uncertainty concerning long-term feedstock availability.

These challenges demonstrate that biomass development requires coordination across the entire supply chain rather than focusing exclusively on conversion facilities.

Future Development of Intelligent Biomass Networks

The combination of optimization, digitalization and improved biomass characterization creates opportunities for more intelligent biomass supply networks. Such networks could integrate information concerning resource availability, feedstock quality, transportation capacity, facility demand and market conditions.

Optimization algorithms could then be used to allocate biomass dynamically across facilities and applications. Digital traceability could provide information about the movement and characteristics of biomass, while monitoring systems could support storage and quality management [61, 66, 71, 96].

Such an approach would represent a transition from static biomass supply chains towards adaptive resource networks. This could be particularly valuable in Malaysia because biomass availability is distributed across multiple agricultural and industrial sectors.

SUMMARY

The selected literature demonstrates that supply-chain management is a fundamental component of biomass-energy development in Malaysia. Biomass must be collected from dispersed sources, transported, stored, preprocessed and delivered to conversion facilities in a manner that is technically reliable and economically feasible [1, 19–25, 55–63].

Optimization methods, including MILP, location-routing approaches and other computational techniques, provide tools for addressing facility location, transportation and resource-allocation decisions. At the same time, aggregation, storage and preprocessing can improve the physical and logistical characteristics of biomass.

Digitalization and traceability provide additional opportunities to improve information management, resource monitoring and coordination across the biomass value chain. These technologies may become increasingly important as biomass systems grow more complex and involve multiple feedstocks, facilities and end markets.
Ultimately, the effectiveness of biomass conversion technologies depends strongly on the supply chain that supports them. A technically capable facility cannot operate sustainably without a reliable feedstock network, while an abundant biomass resource cannot create value unless it can be efficiently mobilized. The next section therefore examines the economic, environmental and social dimensions that determine whether biomass-energy systems can deliver sustainable value beyond their technical performance.

Economic, Environmental And Social Dimensions

Introduction

The development of biomass energy in Malaysia cannot be evaluated solely according to the amount of biomass available or the technical efficiency of individual conversion technologies. The long-term viability of biomass systems depends on the interaction between economic performance, environmental sustainability, social development, energy security and institutional conditions. Biomass resources can create additional value from

agricultural and industrial residues, but their utilization also involves costs associated with collection, transportation, preprocessing, conversion, storage and environmental management [34,51,57,63]. Consequently, biomass energy should be assessed as an integrated system rather than as an isolated energy-generation technology.

The selected literature demonstrates that Malaysian biomass research has progressively moved from simple residue utilization toward higher-value and more integrated applications. These include biofuels, biochemicals, biochar, advanced carbon materials, biogas, syngas, bio-oil and other biomass-derived products [2,26–35,42,45,88–94]. This development reflects the increasing importance of the circular-economy concept, in which residues are treated as resources capable of generating economic, environmental and social value.

Environmental assessment is similarly important. Biomass is renewable in origin, but its environmental performance depends on feedstock sourcing, transportation, processing, energy inputs, emissions, land-use considerations and the treatment of residues and by-products. Life-cycle assessment studies and comparative environmental evaluations therefore provide an important basis for determining whether a particular biomass pathway produces meaningful environmental benefits [78–84,100].

The social dimension is also relevant because biomass resources are frequently located in agricultural and rural areas. The development of collection networks, processing facilities and biomass-based industries can create opportunities for employment, local enterprise and rural economic participation. At the same time, competition for biomass, land-use considerations, changes in existing residue-management practices and unequal distribution of economic benefits can create challenges that require appropriate governance and stakeholder coordination [64–68,85–91].

Economic Value of Biomass Resources

Biomass residues have economic value because they can be converted into energy, fuels, chemicals, materials and other products. The economic potential of biomass is therefore broader than the value obtained from direct combustion for electricity or heat generation. Oil-palm residues, agricultural residues, forestry residues and other lignocellulosic materials can form the basis of multiple conversion pathways, depending on their physical and chemical characteristics [1–5,26–35].

The economic value of biomass is strongly influenced by the distinction between residue availability and usable feedstock availability. A theoretically large biomass resource does not automatically represent a commercially accessible resource. Collection requirements, competing uses, transportation distance, moisture content, storage requirements and preprocessing requirements can substantially influence the delivered cost of biomass [34,51,57,63].

This distinction is particularly important for Malaysia because major biomass resources are distributed across numerous plantations, mills and agricultural locations. The economic value of a residue therefore depends not only on its quantity but also on its location and accessibility. A biomass resource located close to an appropriate conversion facility may have significantly greater practical value than an equivalent resource located far from processing infrastructure.

The literature on biomass utilization also indicates that higher-value applications may provide opportunities to improve the economic performance of biomass systems. Instead of using all available residues exclusively for energy production, integrated systems can allocate different biomass fractions to fuels, chemicals, materials and energy according to their characteristics and market value [2,26–35,42,45,88–94]. Such approaches support a transition from conventional waste disposal toward biomass valorisation.

Feedstock and Logistics Costs

Feedstock acquisition and logistics are among the most important economic considerations in biomass development. Unlike fossil fuels that are generally traded through established energy supply chains, biomass is

often dispersed across agricultural and industrial locations. The costs associated with collection, loading, transportation, unloading, storage and preprocessing can therefore form a substantial component of the overall biomass supply-chain cost [34,51,57,63].

Transportation economics are particularly important because many biomass materials have relatively low bulk density and may contain significant quantities of moisture. Moving untreated biomass over long distances can increase fuel consumption and handling requirements while reducing the economic attractiveness of the feedstock. Consequently, biomass systems require careful coordination between feedstock sources, aggregation facilities and conversion plants.

Preprocessing can improve the logistics characteristics of biomass. Densification, drying, torrefaction and other treatments can reduce handling difficulties and improve storage and transport properties [26–35,42,45]. However, preprocessing itself requires capital investment and energy, meaning that its economic benefits must be evaluated at the overall supply-chain level.

Optimization studies therefore have an important role in determining economically viable biomass networks. Facility-location models, mixed-integer linear programming and other optimization approaches can be used to identify combinations of collection points, transportation routes, processing facilities and conversion plants that improve system performance [1,34,51,57,63]. The economic objective should not be considered independently from environmental and social objectives, particularly when transportation emissions and rural development are included in system assessment.

Capital Investment and Operating Costs

The commercialization of biomass technologies requires consideration of both capital expenditure and operating expenditure. Advanced technologies such as gasification, pyrolysis, hydrothermal conversion, biochemical processing and integrated biorefineries may require specialized equipment, process control systems and supporting infrastructure [26–35,42,45,88–94].

Capital requirements are influenced by the scale and complexity of the facility. Small decentralized systems may reduce transportation distances but may not achieve the same economies of scale as centralized plants. Conversely, large centralized facilities can benefit from larger processing capacities while potentially increasing feedstock collection distances. This creates an important trade-off between scale economies and biomass transportation costs.

Operating costs are similarly affected by feedstock quality, equipment utilization, labour requirements, maintenance, energy consumption and residue management. Technologies that require relatively dry and uniform feedstocks may require additional preprocessing when heterogeneous agricultural residues are used. Therefore, technology selection should be integrated with feedstock availability and supply-chain design rather than being considered independently.

The selected literature on techno-economic assessment and biomass system development [51,57,63,85–91] supports the importance of evaluating complete systems rather than only individual process units. Economic feasibility should consider the interaction between feedstock costs, conversion performance, product revenues, infrastructure requirements and market conditions.

Scale and Economies of Integration

Scale is an important consideration in biomass energy development because increasing facility size can reduce unit costs through improved utilization of equipment and infrastructure. However, biomass differs from conventional centralized energy resources because the feedstock is geographically dispersed. Increasing plant capacity can therefore increase the required collection radius and transportation requirements.

An alternative approach is the development of integrated or distributed biomass systems. Biomass can be collected and partially processed through regional hubs before being transported to larger conversion facilities. This approach can potentially combine the advantages of local collection with centralized conversion.

Integration can also occur at the process level. A biomass facility may produce several outputs from a common feedstock stream, allowing energy products to be combined with higher-value chemicals, materials or carbon-rich products [2,26–35,88–94]. Such integration can diversify revenue sources and reduce dependence on a single product market.

The concept of integration is particularly relevant to Malaysia because oil-palm processing already generates multiple residue streams. Instead of treating each residue independently, an integrated system can potentially coordinate the use of fibres, shells, empty fruit bunches, trunks, fronds and liquid residues according to their respective properties and conversion suitability.

Energy-Only versus Multi-Product Biomass Systems

Conventional biomass energy development often focuses on electricity or heat generation. Although energy production remains important, the selected literature demonstrates increasing interest in multi-product biomass utilization. Biomass can be converted into fuels, chemicals, materials and carbon-based products in addition to electricity and heat [2,26–35,42,45,88–94].

The economic implications of this transition are significant. Energy products generally have established applications, but higher-value products may provide additional economic opportunities where appropriate technologies and markets exist. Bio-succinic acid, biofuels, biochar, advanced carbon materials and other products illustrate the possibility of moving beyond low-value residue disposal toward higher-value biomass utilization [2,42,45,88–94].

However, multi-product systems also involve greater technical complexity. Product purification, quality control, market development and process integration can increase capital and operating requirements. Therefore, diversification should be evaluated on the basis of complete economic and environmental performance rather than assuming that higher-value products automatically produce superior system outcomes.

Biofuels, Biochemicals and High-Value Products

The selected references include several pathways for converting biomass into fuels and chemicals. Research on agricultural-waste-derived syngas, biofuels, biochemical products and biomass-derived materials illustrates the potential for biomass resources to support sectors beyond conventional electricity generation [2,3,26–35,42,45].

Biofuel pathways are particularly relevant to energy-transition discussions because biomass-derived fuels can potentially substitute for portions of fossil fuel consumption. However, their sustainability depends on feedstock sourcing, processing requirements, land-use considerations, transportation and life-cycle emissions [84,90,100].

Biochemical production represents another pathway for increasing the value of biomass. The conversion of oil-palm biomass into bio-succinic acid demonstrates how lignocellulosic residues can become feedstocks for chemical production rather than being used only as low-value fuels [2]. Such pathways support the broader concept of a biomass biorefinery, in which multiple products are generated from a common feedstock platform.

The selected studies on biomass-derived materials further demonstrate that biomass utilization can extend into non-energy applications [88–94]. These applications can contribute to resource efficiency and circularity by retaining carbon and other valuable components in products rather than immediately converting all biomass into energy.

Environmental Sustainability

Biomass energy is often associated with renewable energy because biomass originates from biological resources. Nevertheless, renewable origin alone does not guarantee environmental sustainability. The environmental

performance of biomass systems depends on the entire chain from feedstock production and collection to processing, transportation, conversion and final product use.

Potential environmental benefits include the utilization of residues, reduced dependence on fossil resources, recovery of energy from organic waste and production of useful products from materials that might otherwise be underutilized [26–35,78–84]. Biomass conversion can also support circular resource management by returning selected by-products to agricultural systems or incorporating carbon-rich products into material applications.

Potential environmental burdens include transport emissions, process energy requirements, air emissions, wastewater generation, ash or solid-residue management and impacts associated with feedstock production. These considerations demonstrate why environmental evaluation must be performed at the system level.

The selected literature on life-cycle assessment and environmental performance [78–84,100] indicates the importance of comparing biomass systems with alternative energy and fuel pathways. Such comparisons can reveal trade-offs that are not visible when only direct process emissions or renewable-energy status are considered.

Life-Cycle Assessment

Life-cycle assessment provides a framework for evaluating environmental impacts across multiple stages of a biomass system. For biomass energy, the relevant stages can include feedstock production or generation, collection, preprocessing, transportation, conversion, product distribution and end use.

The selected studies on environmental assessment [78–84] and comparative life-cycle analysis [100] demonstrate the relevance of this approach to Malaysian energy-transition decisions. A biomass pathway may perform differently depending on feedstock type, technology configuration, transportation requirements and system boundaries.

Life-cycle assessment is particularly important when comparing biomass with alternative renewable-energy pathways. The selected study comparing large-scale solar and biodiesel production from palm oil [100] illustrates that renewable-energy technologies can involve different environmental burdens across their life cycles. Therefore, classification as a renewable technology should not replace detailed environmental assessment.

LCA can also support technology selection by identifying environmental hotspots. If transportation contributes significantly to impacts, decentralized preprocessing or facility relocation may be considered. If conversion energy requirements dominate, process integration or energy recovery may be investigated. Thus, environmental assessment can inform engineering and supply-chain decisions rather than functioning only as a reporting exercise.

Carbon and Emissions Considerations

Carbon performance is an important dimension of biomass energy, but it requires careful interpretation. The use of biomass residues does not automatically mean that the resulting energy pathway is carbon neutral. Carbon flows associated with biomass generation, collection, transportation, processing, conversion and final use must be considered within an appropriate system boundary.

Thermochemical processes such as combustion, gasification and pyrolysis generate different emission profiles and carbon-containing products [3,26–35]. The production of biochar or other stable carbon-rich materials may create different carbon-storage implications from pathways that convert biomass completely into energy.

Similarly, biofuel pathways must be evaluated according to their full life cycles rather than only the carbon content of the final fuel. The selected comparative assessment of biodiesel and large-scale solar systems [100] highlights the importance of evaluating energy-transition pathways through broader environmental indicators.

Consequently, carbon assessment should be integrated with feedstock sourcing, technology choice, transportation and product allocation. This is particularly important where biomass resources have competing uses or where land-use effects are involved.

Circular Economy and Resource Efficiency

The circular-economy perspective provides a useful framework for understanding biomass development in Malaysia. Agricultural and industrial residues can be regarded as secondary resources rather than waste streams. Their conversion into energy, chemicals, fuels and materials can reduce resource losses and increase the productivity of existing biological systems [26–35,42,45,88–94].

Oil-palm processing provides a clear example of this potential. Multiple residue streams are generated at different stages of the production chain, creating opportunities for integrated utilization. Energy recovery can be combined with material recovery, biochemical conversion and production of carbon-rich products.

Cascading utilization is particularly relevant. Biomass does not necessarily need to be converted immediately into energy. Where technically and economically appropriate, higher-value material or chemical applications may be prioritized, while lower-value residues and process by-products can subsequently be directed toward energy recovery.

This approach can improve overall resource efficiency, although it requires careful assessment of market demand, technology availability, environmental impacts and competing biomass uses. The circular-economy perspective therefore reinforces the need for integrated planning rather than isolated technology deployment.

Social and Rural Development Dimensions

The social dimension of biomass energy is closely related to the geographic distribution of biomass resources. Agricultural residues are often generated in rural and semi-rural areas, meaning that biomass industries can potentially create economic activities outside major urban centres.

The development of biomass collection, preprocessing, transportation and conversion networks can generate demand for local services and employment. Biomass hubs and decentralized processing facilities may also provide opportunities for local participation in supply-chain activities.

However, the selected literature contains more extensive technical and economic analysis than direct empirical studies of social acceptance, household welfare or community attitudes. Therefore, the social implications should not be overstated beyond what the reviewed evidence supports. Further research is needed to assess how biomass development affects different stakeholder groups and how benefits and costs are distributed.

Social sustainability also requires consideration of existing uses of biomass. Residues may already provide fuel, soil amendments, animal-feed inputs, industrial materials or other economic functions. Diverting these resources into energy systems can therefore affect existing users. Sustainable biomass development requires recognition of these competing uses and meaningful stakeholder participation.

Employment and Local Economic Participation

Biomass supply chains can support employment across several stages, including collection, transportation, preprocessing, equipment operation, maintenance, engineering and facility management. Higher-value biomass industries can also create opportunities for technical skills development and local entrepreneurship.

The extent of employment creation depends on the structure of the biomass industry. Highly automated centralized facilities may generate fewer direct jobs but can create indirect employment through logistics and service industries. More decentralized systems may require greater local involvement in feedstock collection and preprocessing.

The economic benefits of biomass development should therefore be assessed beyond plant-level profitability. Regional value creation, local supply-chain participation and the development of technical capabilities can contribute to the broader economic effects of biomass commercialization.

Nevertheless, employment benefits should be considered alongside labour conditions, occupational safety, skills requirements and long-term job stability. These factors represent areas where additional empirical research could strengthen the social assessment of Malaysian biomass systems.

Stakeholder Coordination and Social Acceptance

Biomass systems involve multiple stakeholders, including plantation operators, farmers, mills, logistics providers, technology developers, energy producers, government agencies and local communities. Effective coordination among these groups is essential because the biomass supply chain extends across multiple ownership and operational boundaries.

Stakeholder coordination is particularly important where biomass has competing uses. A residue that appears to be available at the national level may already be economically utilized by another sector. Consequently, biomass development requires mechanisms for information sharing, contractual coordination and transparent resource allocation.

Digital traceability and supply-chain monitoring can support this process by improving information about biomass origin, quantity, quality and movement [61,66,71,96]. Such systems can contribute to sustainability verification and strengthen confidence among market participants.

Social acceptance may also depend on perceived environmental impacts, local economic benefits and trust in project governance. The selected literature does not provide sufficient evidence to generalize social acceptance across Malaysian biomass projects, indicating a need for more community-level research.

Energy Security and Resilience

Biomass can contribute to energy security by diversifying Malaysia's domestic energy-resource base. Agricultural and industrial residues represent locally generated resources that can potentially be converted into electricity, heat, fuels and other energy carriers [1–5,26–35].

The contribution of biomass to energy resilience is particularly relevant when supply chains are designed to use multiple feedstocks. A multi-feedstock facility may reduce dependence on a single residue stream and potentially improve operational flexibility [34,51,57,63].

However, biomass energy systems also have their own vulnerabilities. Feedstock availability can vary seasonally, logistics can be disrupted, and market competition can change the availability and price of residues. Therefore, energy resilience requires not simply biomass availability but robust supply-chain design, storage capacity, alternative feedstock options and appropriate system planning.

Trade-Offs and System-Level Assessment

Economic, environmental and social objectives can sometimes conflict. For example, increasing plant capacity may improve conversion economics while increasing transportation requirements. Extensive preprocessing may improve feedstock quality while increasing energy consumption and capital costs. Greater biomass extraction may improve energy supply while reducing the availability of residues for existing uses.

These trade-offs demonstrate the importance of multi-dimensional assessment. Techno-economic analysis can determine financial feasibility, while life-cycle assessment can evaluate environmental consequences. Social and institutional analysis can identify stakeholder effects and governance requirements.

A sustainable biomass system should therefore be evaluated using a combination of economic, environmental and social indicators. The selected literature provides components of such an assessment through studies of

optimization, techno-economics, environmental performance, policy and biomass valorisation [34,51,63,78–91,100].

Challenges for Sustainable Commercialization

Several challenges must be addressed before biomass energy can achieve broader and sustained commercialization in Malaysia. First, feedstock costs and availability can vary according to location, season and competing uses. Second, transportation and preprocessing can significantly influence delivered biomass costs. Third, advanced conversion technologies may require substantial investment and technical expertise.

Environmental performance must also be demonstrated through appropriate life-cycle boundaries and credible sustainability indicators. The use of biomass should not be assumed to be environmentally beneficial without considering the complete supply chain.

Social and institutional issues represent another challenge. Effective biomass development requires coordination between producers, processors, logistics providers, technology companies, regulators and local communities. Clear responsibilities and transparent resource-management arrangements can reduce uncertainty and improve project implementation.

Market development is equally important. Higher-value biomass products require reliable markets, quality standards, technological maturity and supporting infrastructure. Without sufficient market demand, technically feasible biomass products may remain difficult to commercialize.

Finally, policy consistency is important for investment decisions. Biomass projects often require long development periods and substantial capital investment. Stable policy frameworks, appropriate incentives and clear sustainability requirements can reduce uncertainty and support private-sector participation [64,73,84,90,95–100].

SUMMARY

The economic, environmental and social dimensions of biomass energy are strongly interconnected. Economic viability depends on feedstock costs, logistics, capital investment, technology performance, scale and product markets. Environmental sustainability depends on feedstock sourcing, transportation, conversion, emissions, resource efficiency and life-cycle impacts. Social sustainability depends on local economic participation, employment, stakeholder coordination, competing biomass uses and equitable distribution of benefits.

The selected literature indicates that Malaysia has opportunities to move beyond simple biomass energy recovery toward integrated systems based on biomass valorisation, biorefineries, advanced conversion technologies, circular resource use and multi-product production [2,26–35,42,45,88–94]. At the same time, commercialization requires system-level assessment because no individual technological pathway can be considered sustainable independently of its feedstock supply chain and wider environmental and socioeconomic context.

A balanced biomass strategy should therefore combine techno-economic analysis, life-cycle assessment, supply-chain optimization, stakeholder considerations and policy analysis. Such an integrated approach can support the development of biomass systems that utilize Malaysia's substantial biological resources while reducing waste, creating economic value and contributing to broader energy-transition objectives.

Policy, Governance And Commercialization

Introduction

The development of biomass energy in Malaysia is influenced not only by technological capability and resource availability but also by policy, institutional coordination, market conditions and commercialization mechanisms. Biomass resources are distributed across agricultural, plantation, forestry and industrial systems, meaning that their development involves multiple sectors and stakeholders. As a result, the transition from technically feasible

biomass applications to commercially established systems requires coordination between energy policy, agricultural resource management, environmental regulation, industrial development and investment frameworks [64,73,84,90,95–100].

The selected literature indicates that Malaysia's biomass development should be understood within the broader context of renewable-energy development and energy transition. Policy decisions influence investment conditions, technology adoption, market opportunities and the sustainability requirements applied to biomass resources. At the same time, the effectiveness of policy depends on the availability of appropriate technologies, reliable feedstock supply chains and commercially viable end products.

Biomass within Malaysia's Energy Transition

Biomass represents one component of Malaysia's broader transition toward a more diversified and sustainable energy system. Unlike intermittent renewable resources whose output depends strongly on weather conditions, biomass can potentially provide dispatchable energy when sufficient feedstock and storage infrastructure are available.

The role of biomass extends beyond electricity generation. Biomass can contribute to renewable fuels, industrial heat, biogas, biochemical production and material substitution [2,26–35,42,45]. This diversity allows biomass policy to interact with several areas of energy and industrial policy simultaneously.

However, the energy-transition role of biomass should be evaluated according to specific feedstocks and applications rather than assuming that all biomass pathways provide identical benefits. The comparative life-cycle assessment of solar and biodiesel pathways illustrates the importance of considering environmental performance when evaluating alternative energy-transition options [100].

Policy Support and Investment Conditions

Commercial biomass development generally requires a policy environment that reduces uncertainty and encourages investment. Biomass facilities can involve substantial capital expenditure, long project-development periods and exposure to feedstock and product-market risks. Investors therefore require sufficient confidence in resource availability, market conditions, regulatory requirements and long-term policy direction.
The selected literature addressing renewable-energy development and Malaysian energy-transition issues [64,73,84,90,95–100] demonstrates the importance of policy frameworks in shaping renewable-energy deployment. Policy instruments can influence technology adoption, investment incentives, environmental requirements and market access.

For biomass specifically, policy support should consider the characteristics of the entire supply chain. Incentives directed only at electricity generation may not address bottlenecks in biomass collection, transportation, preprocessing or storage. Similarly, support for advanced conversion technologies may have limited impact if reliable feedstock supply has not been established.

Institutional Coordination

Biomass development crosses traditional administrative and industrial boundaries. Agricultural agencies may influence residue generation and management, energy institutions may regulate energy production, environmental authorities may establish sustainability requirements, while industrial stakeholders operate processing and conversion facilities.

This creates a need for institutional coordination. Fragmented decision-making can increase administrative complexity and create uncertainty for project developers. Integrated planning can instead align biomass resource management, energy development, environmental protection and industrial policy.

The selected literature's emphasis on biomass optimization, supply chains, traceability and energy-transition policy [34,51,61,66,71,73,84,95–100] supports the importance of coordinated governance. Digital information systems may further assist institutions by improving visibility of biomass flows and supporting monitoring and verification.

Regulatory Considerations for Biomass Feedstocks

Regulatory treatment of biomass can influence whether a material is considered a waste, residue, by-product or commercially valuable resource. This classification can affect handling requirements, environmental responsibilities, marketability and the feasibility of utilization pathways.

Clear resource classifications can help reduce uncertainty for biomass developers. At the same time, regulation must ensure that biomass extraction does not create unintended environmental consequences. For example, removing agricultural residues from fields may affect existing soil-management practices, while intensive extraction from industrial systems may alter the availability of materials for existing users.

A sustainable regulatory framework should therefore distinguish between genuinely underutilized residues and biomass resources that already perform important environmental or economic functions.

Sustainability Governance

Sustainability governance is increasingly important as biomass systems move toward larger commercial scales. Sustainability assessment should address feedstock origin, resource availability, transportation, conversion, emissions, waste management and final product use.

Life-cycle assessment provides one mechanism for evaluating these issues, while digital traceability can provide information on the physical movement and origin of biomass [61,66,71,78–84,96]. Combining these approaches can strengthen the transparency of biomass supply chains.

Sustainability governance is especially important for biomass pathways connected to internationally traded fuels, chemicals and materials. Buyers and regulators may require evidence that products meet environmental and resource-management standards. Consequently, traceability can become not only an environmental-management tool but also a commercial requirement.

Certification and Traceability

Traceability systems can improve confidence in biomass supply chains by recording information about feedstock origin, quantity, quality and movement. The selected literature on digitalization and traceability [61,66,71,96] indicates that digital technologies have potential to strengthen supply-chain management.

A traceability system can potentially connect information from biomass producers to aggregation points, transportation providers, processing facilities and final conversion plants. Such systems can support quality control, inventory management and sustainability verification.

The usefulness of traceability, however, depends on data quality and stakeholder participation. A technically advanced system will provide limited benefits if information is incomplete, inconsistent or not shared between supply-chain participants. Governance arrangements must therefore establish responsibilities for data collection, verification and access.

Market Development

Commercialization requires more than technological feasibility. Biomass-derived products must have reliable markets, competitive costs and sufficient quality. This is particularly important for advanced products such as biofuels, biochemicals, biochar and biomass-derived materials [26–35,42,45,88–94].

Energy products may benefit from established energy markets, whereas emerging biomass-derived products may require new market-development strategies. For example, biochemical and advanced-material applications require customers capable of purchasing products according to appropriate technical specifications.

Market development can therefore be supported through standards, demonstration projects, industrial partnerships and long-term purchasing arrangements. These mechanisms can reduce uncertainty during the transition from laboratory or pilot-scale production toward commercial deployment.

Commercialization of Advanced Biomass Technologies

The selected references cover a broad range of technologies, including gasification, pyrolysis, torrefaction, hydrothermal conversion, biochemical production and advanced material applications [3,26–35,42,45,88–94]. These technologies differ considerably in technical maturity, capital requirements and market readiness.

Commercialization requires progressive movement through development stages. Laboratory-scale studies can demonstrate technical feasibility, but pilot-scale testing is needed to identify operational challenges. Demonstration facilities can then provide information about feedstock variability, equipment reliability, product quality and real-world economics.

The transition between these stages can be difficult because scale-up may reveal challenges that are not visible under controlled laboratory conditions. Therefore, commercialization strategies should include long-term pilot operation, supply-chain testing and integrated techno-economic and environmental assessment.

Public and Private Sector Roles

Both public and private actors have important roles in biomass development. Public institutions can provide policy direction, infrastructure support, research funding, regulatory frameworks and sustainability standards. Private companies can contribute investment, technology development, operational expertise and market access. Research institutions also have an important role in bridging technical development and commercial application. Collaboration between universities, technology developers, biomass producers and industrial users can accelerate knowledge transfer.

The selected literature's broad coverage of technical, economic, environmental and policy issues [1–100] demonstrates that biomass development is inherently interdisciplinary. Effective commercialization therefore requires collaboration across academic, industrial and governmental institutions.

Financing and Investment Risk

Biomass projects can face several forms of investment risk. Feedstock availability may change over time, biomass prices can be influenced by competing industries, and technology performance may differ between pilot and commercial scales. Product markets can also be uncertain for emerging biomass-derived products.
Financial assessment should therefore include sensitivity to feedstock costs, transportation distances, plant utilization, product prices and technology performance [34,51,57,63,85–91]. Risk analysis can help identify the variables that have the greatest influence on project viability.
Policy stability can also affect financing conditions. Long-term projects require confidence that relevant incentives, regulations and sustainability requirements will remain sufficiently predictable throughout the investment period.

Policy Support for Supply-Chain Development

Policy interventions should not focus exclusively on the conversion facility. Feedstock collection and logistics represent critical components of biomass commercialization. Support for aggregation centres, preprocessing

facilities, storage infrastructure and transportation systems may therefore be necessary to establish reliable biomass markets.

Supply-chain optimization studies [1,34,51,57,63] demonstrate that the location and configuration of facilities influence overall system performance. Policy planning can incorporate these findings by encouraging biomass infrastructure in areas where sufficient resource density and market demand exist.

Regional biomass hubs may provide one mechanism for connecting dispersed producers with larger conversion facilities. Such infrastructure can reduce transaction costs, improve feedstock quality and facilitate more consistent supply.

Policy and Circular-Economy Development

Biomass policy can also support Malaysia's transition toward a more circular economy. Instead of treating agricultural and industrial residues as waste-management problems, policy can encourage their productive use in energy, chemicals, fuels and materials [26–35,42,45,88–94].

Circular-economy policy should nevertheless recognize the hierarchy of possible biomass uses. Not every residue should automatically be directed toward energy generation. Higher-value applications may provide greater resource efficiency in some circumstances, while residual materials can subsequently be used for energy recovery.

Policy frameworks can therefore encourage cascading utilization and integrated biomass systems. Such approaches can promote resource efficiency while reducing competition between energy and material applications.

Policy Challenges Associated with Competing Biomass Uses

Biomass markets can create competition between different industries. The same residue may have potential applications in electricity generation, process heat, pellet production, animal-related applications, soil management, material production or biochemical conversion.

This competition means that policies promoting one application may unintentionally affect another sector. Sustainable governance should therefore evaluate biomass demand across the wider economy rather than treating individual applications in isolation.

Optimization models can contribute to this process by evaluating alternative allocations of biomass among competing uses [1,34,51,57,63]. Such analysis can support more transparent resource-allocation decisions.

Regional Development and Decentralized Biomass Systems

Because biomass resources are distributed geographically, decentralized systems may have an important role in regional development. Smaller facilities or regional preprocessing centres can reduce the distance between feedstock sources and initial processing activities.

Such systems may also enable local businesses and communities to participate in biomass supply chains. However, decentralization can reduce economies of scale and increase the number of facilities requiring management and maintenance.

The appropriate balance between centralized and decentralized development therefore depends on feedstock density, transportation costs, technology scale, local infrastructure and market conditions. Supply-chain optimization provides a basis for evaluating these alternatives.

Digital Governance and Industry

Digital technologies offer opportunities to improve biomass governance and commercialization. Sensors, databases, geographic information systems, digital platforms and traceability systems can improve information about biomass quantities, quality, location and movement [61,66,71,96].

Such technologies can support real-time inventory management, transportation planning and sustainability monitoring. They can also facilitate coordination between dispersed biomass suppliers and conversion facilities. The development of digital biomass systems is consistent with the broader movement toward Industry 4.0. However, implementation requires appropriate data standards, technical skills, infrastructure and stakeholder participation. Digitalization should therefore be treated as an enabling component of biomass governance rather than a replacement for institutional coordination.

Alignment with Environmental Policy

Biomass commercialization should be consistent with environmental objectives. Conversion facilities must manage emissions, wastewater, solid residues and other environmental impacts appropriately. At the same time, feedstock extraction should not undermine ecological functions or existing resource-management practices.

Life-cycle assessment can help align biomass development with environmental objectives by evaluating impacts across the complete system [78–84,100]. Environmental policy can then establish minimum requirements while allowing technology developers flexibility in selecting appropriate technical solutions.
The combination of regulation, monitoring and life-cycle assessment can support a more evidence-based approach to biomass sustainability.

Barriers to Commercial Deployment

Despite substantial research activity, several barriers can prevent successful commercial deployment. These include:

1. Feedstock uncertainty: Biomass availability and quality can vary spatially and temporally.
2. Logistics costs: Collection and transportation can reduce economic competitiveness.
3. Technology risk: Advanced processes may require further scale-up and demonstration.
4. Capital requirements: Commercial facilities require substantial upfront investment.
5. Market uncertainty: Emerging biomass products may lack established demand.
6. Policy uncertainty: Changes in incentives or regulations can affect investment decisions.
7. Institutional fragmentation: Multiple agencies and stakeholders can complicate project development.
8. Competing uses: Biomass may already have established economic or environmental functions.
9. Sustainability verification: Commercial markets may require increasingly detailed evidence of responsible sourcing.
10. Technical skills: Advanced biomass systems require specialized engineering, operational and digital capabilities.

These barriers are interconnected. For example, uncertain feedstock supply can increase financial risk, while limited markets can reduce investment in new conversion technologies. Consequently, isolated interventions may have limited effectiveness.

Strategies for Commercialization

A coordinated commercialization strategy should combine technology development, supply-chain strengthening, market creation and policy support. Demonstration projects can provide practical information about technology performance and supply-chain reliability. Biomass hubs can improve resource aggregation, while digital systems can strengthen traceability and inventory management.

Policy mechanisms can also encourage partnerships between biomass producers, technology providers and energy or industrial users. Long-term supply agreements may reduce feedstock uncertainty, while long-term product agreements may improve investment confidence.

For advanced biomass products, commercialization strategies should also include standards development and market education. These measures can help establish confidence in product quality and support adoption by industrial customers.

Towards an Integrated Biomass Governance Framework

The evidence reviewed across the selected references suggests that biomass governance should be designed as an integrated system connecting five major components:

Resource management → Supply-chain coordination → Technology deployment → Market development → Sustainability governance

Resource management determines what biomass can be sustainably supplied. Supply-chain coordination connects dispersed resources with processing facilities. Technology deployment determines how biomass can be converted or valorised. Market development determines whether resulting products can generate economic value. Sustainability governance ensures that environmental and social requirements are incorporated throughout the system.
Digital traceability and data management can operate across all five components, supporting transparency and coordination [61,66,71,96].
Such an integrated framework is more appropriate than policies that address electricity generation, agricultural residues, environmental regulation or industrial development separately. Biomass is inherently cross-sectoral, and its governance should reflect this characteristic.

Future Policy Priorities

Several policy priorities emerge from the reviewed literature. First, biomass resource assessment should be continuously updated to reflect changes in production, competing uses and technology. Second, supply-chain infrastructure should be developed in locations with sufficient sustainable resource density.

Third, policy should support technology demonstration and scale-up, particularly for advanced conversion and valorisation pathways. Fourth, life-cycle and sustainability assessment should be incorporated into decision-making to avoid transferring environmental burdens between different stages of the biomass system.

Fifth, digital traceability should be encouraged to improve resource transparency and sustainability verification. Finally, policy development should consider the economic participation of rural stakeholders and the distribution of benefits across biomass supply chains.

Summary

Policy, governance and commercialization are essential to translating Malaysia's biomass resource potential into sustained industrial and energy applications. Technology alone cannot establish a functioning biomass industry. Reliable feedstock supply, appropriate logistics, investment conditions, markets, institutional coordination and sustainability governance are equally important.

The selected references demonstrate the increasing breadth of Malaysian biomass research, extending from resource management and conversion technologies to optimization, environmental assessment, digitalization and energy-transition policy [1–100]. This body of work supports the development of integrated policy approaches that recognize biomass as both an energy resource and a platform for circular-economy development.

Future biomass policy should therefore move toward coordinated resource planning, supply-chain development, technology commercialization, digital traceability and life-cycle sustainability assessment. Such an approach can provide a stronger foundation for the next stage of Malaysia's biomass-energy development.

CONCLUSION

Biomass energy has significant potential to contribute to Malaysia's renewable-energy development, particularly through the utilization of oil-palm residues, agricultural waste, forestry resources and other biomass feedstocks. However, the availability of biomass alone does not guarantee successful development. Feedstock characteristics, collection, transportation, storage, technology selection and competing uses must be considered together.

The review shows that Malaysia has opportunities to move beyond conventional biomass combustion toward more diversified applications, including gasification, pyrolysis, biogas, biofuels, biochemicals, biochar and biomass-derived materials. Integrated and higher-value utilization can improve resource efficiency and support circular-economy development.

Economic and environmental performance are also central to long-term viability. Biomass systems must address supply-chain costs, investment requirements, market conditions and life-cycle environmental impacts. Policy support, institutional coordination, digital traceability and effective supply-chain management are equally important for commercial development.

Overall, sustainable biomass development in Malaysia requires a coordinated approach that connects available resources with appropriate technologies, efficient supply chains, viable markets and environmental safeguards. With effective planning and continued technological development, biomass can contribute not only to renewable-energy generation but also to resource efficiency, industrial development and the broader transition toward a more sustainable and circular economy.

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