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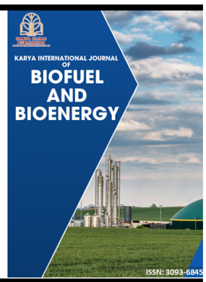

Valorizing Agricultural Residues for Biomass-to-Bioenergy in Malaysia: Insights into Opportunities, Challenges, and Strategic Pathways

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ABSTRACT

Malaysia generates a significant volume of biomass residues, notably from its oil palm and pineapple industries. However, the full potential remains untapped due to fragmented value chains, underdeveloped infrastructure, technological gaps, and policy misalignment. While numerous studies have discussed biomass availability and bioenergy technologies, few have critically integrated these elements with commercialization potential and circular economy frameworks specific to Malaysia's context. Despite Malaysia's high biomass potential, a lack of communication and alignment between researchers and stakeholders has hindered the realization of the circular economy via the valorization of agricultural waste. It aims to contribute to the successful commercialization of Malaysian biomass-to-bioenergy initiatives by aligning technical insights with strategic priorities. This paper addresses this gap by systematically evaluating the types and status of biomass-to-bioenergy technologies based on technological readiness level (TRLs), assessing structural challenges through a SWOT analysis. The paper also proposes a commercialization roadmap from 2025 to 2040, to anchor biomass-to-bioenergy realization from the perspective of researchers. This paper offers strategic pathways to unlock biomass value through decentralized bioenergy systems, co-product valorization, and regional trade integration.

1. Introduction

Biomass-to-bioenergy refers to the suite of technological processes that convert organic materials, primarily lignocellulosic residues from agriculture and forestry into usable energy carriers such as electricity, heat, biogas, or liquid biofuels. These conversion pathways include thermochemical (e.g. combustion, gasification), biochemicals (e.g., anaerobic digestion, fermentation), and physicochemical routes. Within the context of a circular economy [1], biomass valorization plays a pivotal role in minimizing waste [2], enhancing resources efficiency, and substituting fossil-based inputs with renewable alternatives. The integration of biomass-to-bioenergy systems into national energy strategies is recognized as a key component of low-carbon development and sustainable resource management [3].

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A circular bioeconomy integrates biological resources (such as crops, residues, and organic waste) into value-added production systems that are regenerative, low-emission, and waste-minimizing or zero-waste [1]. The concept combines the principles of a bioeconomy (utilizing renewable biological resources) with the logic of circular economy (recycling, reusing and extending resource value). Figure 1 illustrates the overview of the concept.

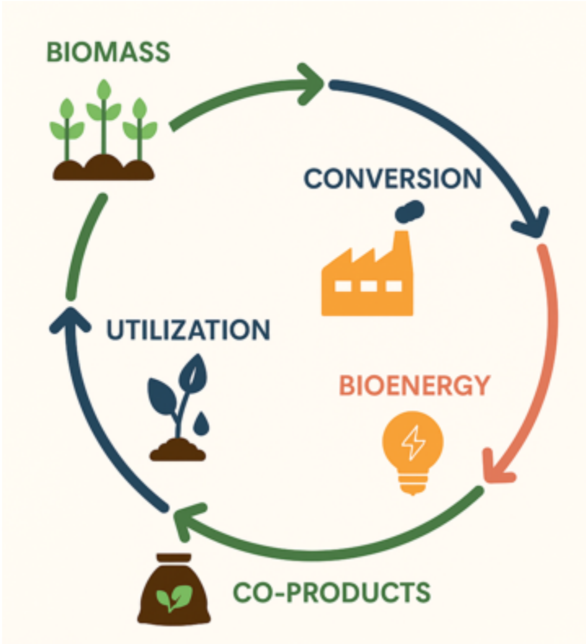

Fig. 1. Conceptual diagram of a circular bioeconomy model for biomass-to-bioenergy system

Moving toward a circular bioeconomy is both timely and strategic for achieving climate goals and ensuring energy security. Key alignment for this transition to the United Nations Sustainable Development Goals (SDGs) [4] includes:-

i. SDG 7 - Affordable and Clean Energy: Biomass-based energy systems, particularly when deployed in off-grid power generation systems, offer an accessible and renewable alternative to fossil-derived electricity in rural and off-grid regions.
ii. SDG 12-Responsible Consumption and Production: Valorization of agricultural residues through bioconversion technologies facilitates the creation of closed-loop resource systems.
iii. SDG 13 – Climate Action: Biomass-to-bioenergy pathways contribute to climate mitigation by replacing fossil fuels with carbon-neutral alternatives and enabling carbon sequestration.
iv. SDG 9- Industry, Innovation and Infrastructure: The scaling of biomass conversion technologies, from pilot-scale biorefineries to industrial bioenergy production, stimulates innovation and infrastructure development in the bioeconomy.
v. SDG 8 - Decent Work and Economic Growth: The bioenergy sector holds significant potential for generating inclusive and sustainable employment opportunities across the value chain. The chain begins with biomass collection and preprocessing and extends to system operation and marketing of co-products.

2. Biomass Availability and Utilization in Malaysia

Malaysia's agro-industrial economy produces a wide array of biomass resources, with the oil palm sector being the dominant contributor. Biomass resources are distributed across various locations, including plantations, mills, timber operations, rice fields, and even municipal sources. However, a significant portion of this biomass remains underutilized despite its potential in renewable energy and circular bioeconomy [5].

2.1 Biomass Sources and Quantities

The total available agricultural biomass in Malaysia is estimated to exceed 90 million dry tonnes annually as reported by MPC, 2023. Timber operations contribute 3.6 million tonnes of biomass, mainly from rubberwood and sawmill residues [7]. The rice sector yields 2.5 million tonnes of rice husk and straw annually, while municipal solid waste (MSW) generation in Malaysia is around 1,200 tonnes per day. Table 1 summarize biomass availability in Malaysia.

Table 1
Estimated annual quantity of different biomass in Malaysia

Biomass Type	Source	Estimated Annual Quantity (million tonnes)	Reference
Oil Palm Fronds (OPF)	Plantation pruning/replanting	59.6 (dry)	[6]
Oil Palm Trunks (OPT)	Replanting of oil palm tress	7.2 (dry)	[6]
Empty Fruit Bunches	Palm oil mills	20	[6]
Mesocarp Fibre	Palm oil mills	10	[6]
Palm Kernel Shells	Palm oil mills	5	[6]
POME (wet)	Oil extraction process	50 (wet)	[6]
Timber residues	Logging and sawmill processing	3.6	[7]
Rice husks/straw	Paddy farming	2.5	[6]
Municipal Solid Waste	Urban municipalities	~0.44	[5]
Livestock and Fishery Waste	Poultry, cattle, and aquaculture	4.9	[6]

2.2 Utilization Practices in Palm Oil Mills

The following biomass utilization practices in Malaysia mainly is practiced by palm oil mills. Table 2 summarizes the utilization practice mode on a total of 237 mills in Peninsular Malaysia based on biomass types as revealed by Ahmad *et al.*, [5].

Table 2
Biomass utilization practices in palm oil mills [5]

Biomass Type	Average Generation per Mill	Utilization Practice	Share of Mills (%)	Profitability (RM/tonne)
Empty Fruit Bunches (EFB)	39,123 tonnes/year	Returned to plantation; landfilled; sold; limited incineration	41.2% (returned), 21.2% (landfilled), 18.2% (sold)	Up to 153 (incineration)
Mesocarp Fibre (MF)	-	Combusted in in-house boilers	92.4% (in-house use)	34.64 (in-house), 5.59 (external sales)

Table 2 ***(Continued)***

Palm Kernel Shells (PKS)	-	**In-house fuel or sold (domestic/export)**	**67.9% (in-house), 30.3% (sold)**	**175.63 (sales)**
Palm Oil Mill Effluent (POME)	147,778 m^3/year	Used as biofertilizer; small portion sold	80% (internal use), 1.1% (sold)	Not significant

2.3 Challenges in Biomass Utilization

Malaysia generates vast quantities of biomass, but several technical and systemic limitations prevent its optimal utilization within the energy and bio-based product value chain. Biomass residues, such as OPF and OPT, are predominantly left on-site due to their bulkiness, high water content, and the lack of an economically viable transport and pre-processing system [6]). As mesocarp fibre and kernel shells are used on site, other high-volume residues, such as OPF, OPT, and cocoa pod husks, are still underutilized due to a lack of dedicated, large-scale conversion facilities [5]. Though, biomass-derived products are increasingly in demand, such as pellets and biofertilizer, but inefficient supply chain coordination results in inconsistent biomass utilization. Some feedstocks, such as EFB, are challenging to process due to their high silica content and moisture levels , which limit their suitability for direct combustion, gasification, or biogas generation without pre-treatment, such as torrefaction or drying [8]. Despite the fact that some research and development has been done previously, the majority of technology development remains at a lower level of readiness (TRL of 4 to 6), with minimal transition to demonstration or commercial-scale deployment due to limitations of financial abilities [9,10].

3. Biomass-to-Bioenergy Technologies in Malaysia : Status and Readiness

Biomass conversion in Malaysia involves a broad range of process categories, categorized into thermochemical, biochemical, and hybrid routes. These technologies play a pivotal role in transforming various biomass feedstocks, such as oil palm residues, rice husk, municipal solid waste, and animal waste, into bioenergy carriers, including biogas, syngas, bio-oil, and solid biofuels like char and pellets.

3.1 Thermochemical Technologies

Combustion and gasification are most mature thermochemical technologies applied in Malaysia as reviewed by Chan *et al*., [11]. Combustion is primarily employed for heat and electricity production in palm oil mills, using mesocarp fibre and PKS as fuels . In contrast, gasification, although promising for higher energy efficiency and cleaner emissions, remains limited to pilot or semi-commercial scale due to technical and feedstock preparation challenges.

Pyrolysis and hydrothermal carbonization (HTC) offer pathways to produce liquid fuels and biochar, but these are still in R&D or demonstration stages [12,13]. For instance, HTC has demonstrated the ability to process high-moisture feedstocks like food waste and POME sludge into hydro char, making it suitable for nutrient recovery and soil improvement [13]. However, high capital costs, pre-treatment requirements, and unstandardized quality of outputs hinder broader adoption [14].

3.2 Biochemical Technologies

Anaerobic digestion (AD) is widely adopted in palm oil mills for POME treatment, contributing to biogas generation and greenhouse gas mitigation. However, broader deployment is constrained by issues such as inconsistencies of microbe behaviour, slow degradation kinetics , and resistance to AD plant near residential zones [13,15]. AD system in Malaysia typically operate at mesophilic temperature (35 - 37°C) and require careful feedstock particle size control to maintain gas yield (~300 to 450 ml CH_4/g-VS) [15].

Fermentation technologies, including ethanol and hydrogen production via microbial action, remain largely limited to lab-scale or academic trials, primarily due to the complexity of lignocellulosic breakdown, high enzyme costs, and process instability [16,17]. Pretreatment techniques such as alkali, acid hydrolysis and fungal degradation among established method to enhance the saccharification yield [18].

3.3 Hybrid and Emerging Configurations

A shift toward hybrid and integrated energy configurations is occurring in Malaysia's biomass sector with the aim of decarbonizing and increasing efficiency. Using multiple technologies-including thermochemical conversion, electrochemical generation, and solar-assisted processing-these systems maximize energy recovery, reduce emissions, and enhance system resilience. According to Kaur *et al*., [19], recent developments emphasize hybrid systems such as:

- Combined biogasification with solid oxide fuel cells (SOFCs), enabling highly efficient cogeneration;
- Hybrid solar PV-biomass electrolysis systems, which use renewable electricity to generate hydrogen while biomass provides carbon-neutral fuel;
- A polygeneration platform combines heat, power, and bio-based chemicals production in one system.

These configurations provide considerable benefits regarding energy diversification, load balancing, and reducing lifecycle emissions. For example, PV-integrated gasification can lessen dependence on grid electricity while enhancing the efficiency of biomass reforming processes. However, these systems are still at a low Technology Readiness Level (TRL 3-5), with challenges in scaling and integration into Malaysia's energy and waste management frameworks.

3.4 Matching Feedstocks with Conversion Technologies

Malaysia's biomass sector faces a critical challenge due to feedstock-technology mismatches. For example, high-moisture POME is ideal for AD, while low-moisture lignocellulosics such as OPF and EFB require pre-drying before pyrolysis. The variability in particle size, ash content, and volatile matter also demands customized process designs and modular plant configurations for effective energy recovery.

3.5 Current Status and Deployment Readiness

The practical implementation of biomass-to-bioenergy technologies in Malaysia varies significantly depending on the technological pathway, type of feedstock, and regional infrastructure. While certain systems, such as direct combustion in palm oil mills, are widely deployed and operational, others, including pyrolysis, fermentation, and gasification, remain at the developmental or pilot stage [13]. To evaluate the commercialization potential of these technologies, TRL scale as accepted by MOSTI (2025), that are:

- TRL 1: Basic research begins; fundamental principles are observed.
- TRL 2: Concept is formulated; potential applications are identified.
- TRL 3: Experimental proof of concept is established at lab scale.
- TRL 4: Feasibility demonstration through lab-scale development and integration.
- TRL 5: Technology development with focus on production and techno-economic modeling.
- TRL 6: Viability demonstration via scale-up and pilot-scale validation.
- TRL 7: Commercial transition starts; detailed engineering and plant design are developed.
- TRL 8: Semi-commercial demonstration in operational environments.
- TRL 9: Full commercial deployment; technology is operational at market scale.

Table 3 depicted the TRL level for selected technologies, based on the typical feedstock [5,16,17], [18,20]. Assessing TRLs helps policymakers and investors prioritize support mechanisms and guide research-to-commercialization pathways in national biomass strategies.

Table 3
TRL level for selected technology

Technology	Commercial Readiness in Malaysia	Typical Feedstock	TRL Range
Combustion (boilers)	Commercial (common in oil palm mills)	MF, PKS, EFB	8–9
Anaerobic Digestion	Commercial (limited to POME systems)	POME, livestock waste	7–8
Gasification	Demonstration/Pilot	PKS, wood chips, MSW	5–6
Pyrolysis	Pilot scale	EFB, sawdust, PKS	4–6
Hydrothermal Carbonization	R&D/Pilot	Food waste, sludge	3–5
Fermentation (bioethanol)	Lab scale	OPF hydrolysate, starch-rich waste	3–4

4. SWOT Analysis: Biomass-to-Bioenergy Sector in Malaysia

It is imperative to understand the systemic factors that either enable or constrain Malaysia's biomass-to-bioenergy sector. By analyzing strengths, weaknesses, opportunities, and threats, a SWOT analysis provides a strategy for evaluating sector-specific internal capacities and external factors. This information is particularly useful in guiding technology investment decisions, infrastructure development, and policy formulation.

Malaysia's extensive oil palm and agro-industrial sectors provide a comparative advantage in biomass production. However, due to logistical, technical, and policy barriers, actual utilization rates remain limited. At the same time, the country stands at a pivotal moment, with emerging green financing mechanisms and decentralization trends generating new momentum. Understanding these dynamics is critical for stakeholders aiming to scale up sustainable and circular bioenergy solutions. Figure 2.

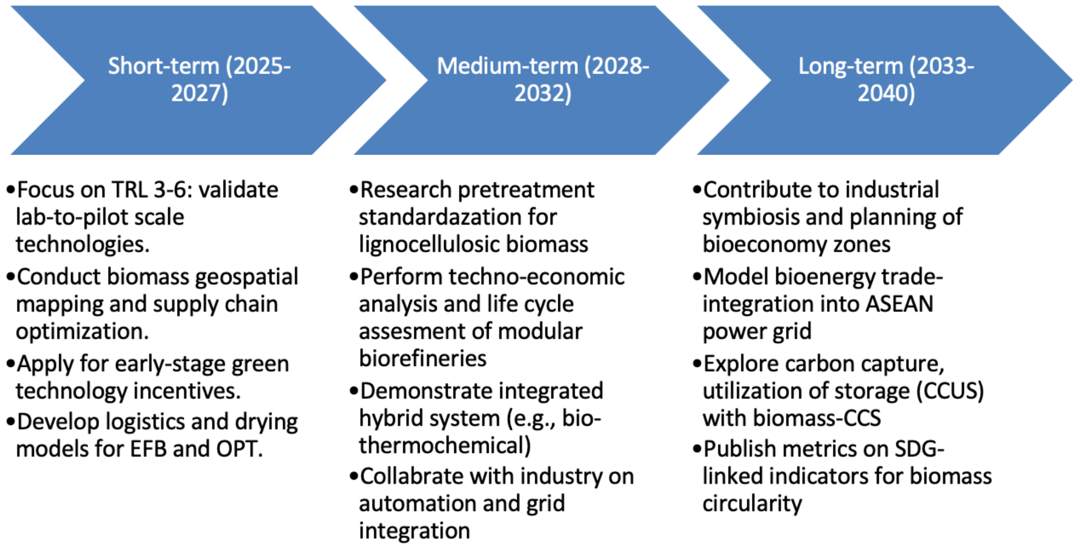

Fig. 2. SWOT analysis of biomass-to-bioenergy sector in Malaysia

5. Commercialization Roadmap – Researcher Perspective

Malaysia's pathway to a sustainable and economically viable biomass-to-bioenergy industry requires a structured and phased commercialization strategy. The proposed roadmap provides a structured framework that aligns biomass research efforts with national energy transition targets, Technology Readiness Levels (TRL), and commercialization pathways. From a research standpoint, the commercialization of biomass-to-bioenergy technologies in Malaysia is not merely a transition from lab to market. It is a multidimensional process involving validation, policy alignment, infrastructure readiness, and socio-environmental consideration. Each commercialization phase presents unique research opportunities, ranging from basic feedstock characterization and TRL scaling in the short term to techno-economic integration and circular economy modeling in the long term. The roadmap detailed in Figure 3 provides a strategic pathway for researchers to contribute meaningfully to Malaysia's biomass valorization journey, ensuring scientific relevance, policy impact, and economic feasibility. The roadmap was constructed based on comprehensive reviews and research done in Malaysia [9,11,14,16,21].

4. Conclusions

Collectively, this paper emphasizes that the insights of successful biomass-to-bioenergy commercialization in Malaysia will require more than technological innovation. It demands coordinated governance, inclusive stakeholder engagement, robust policy instruments, and sustained research commitment. Insights gathered through researchers' ongoing interactions with policymakers, industry players, and local communities reveal a shared recognition of the need for practical alignment between on-the-ground biomass potential, regulatory mechanisms, and investment readiness. This paper highlights the need to develop deployment strategies that are economically scalable, socially acceptable, and tailored to the Malaysian region. With the proper strategic alignment and cross-sectoral collaboration, Malaysia is well-positioned to emerge as a regional leader in the utilization of tropical bioresources and low-carbon development.

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