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Biomass Waste-Based Hydrogen Production: a Review of its Potential in Malaysia

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Malaysia generates an estimated 182.6 Mt of biomass annually that can be harnessed for hydrogen production. However, the commercial deployment of biomass-based hydrogen technologies in Malaysia remains limited, hindered by technological and logistical challenges. The objectives of this review are to highlight key biomass types available in Malaysia such as oil palm residues, rice husk, rice straw and sugarcane bagasse, explore relevant thermochemical and biochemical conversion technologies, and identify its strategic implications. Among them, oil palm biomass remains the most significant for its abundance and potential, with by-products like palm oil mill effluent (POME), empty fruit bunches (EFB), mesocarp fibre and palm kernel shells. Thermochemical methods, like gasification and pyrolysis are suitable for dry lignocellulosic feedstocks like EFB and rice husk, while biochemical routes such as dark fermentation are effective for wet organic waste like POME. By leveraging diverse biomass streams through targeted technology applications and aligning with Malaysia's Hydrogen Economy and Technology Roadmap, Malaysia can advance its hydrogen economy using locally available resources. The review outlines that strategic utilisation of biomass waste can contribute to the Malaysia's green hydrogen economy, supporting local resource strengths while mitigating climate change and securing national energy.

1. Introduction

Hydrogen is increasingly recognised as a clean and adaptable energy carrier for the future and producing hydrogen from renewable resources has gained global interest. Countries like Japan and the European Union (EU) have strongly integrated hydrogen strategies into their energy transition frameworks. For example, Japan aims to become a "hydrogen-based society," with dedicated investments in hydrogen production (METI, 2023), storage, and fuel cell infrastructure (Giakoumakis and Sidiras, 2025). Meanwhile, the EU's Hydrogen Strategy prioritises renewable hydrogen as a pillar for achieving carbon neutrality by 2050, focusing on green hydrogen from water electrolysis and biomass (European Commission, 2020). However, achieving carbon neutrality requires hydrogen to be produced without CO_2 emissions or with captured and stored CO_2 (Kolaczkowski et al., 2023). These global moves highlight the importance of hydrogen as a low-carbon fuel, particularly when it is derived from renewable sources like biomass waste or organic residues from industry, agriculture and forestry (Chandrasekhar et al., 2020).

According to Zakaria et al. (2024), Malaysia as a main palm oil producer, generates a huge quantity of biomass waste. In fact, Malaysia produces nearly half of global palm oil output, generating large amount of biomass waste that results in large amounts of residues such as palm oil mill effluent (POME), palm kernel shells (PKS), empty fruit bunches (EFB), palm fronds, shells, trunks, and other of its waste (Cheng and Cheng, 2018). Every year, over 90 Mt of dry solid oil palm biomass are produced annually in Malaysia (Santani, 2024). Aziz and Hanafiah (2020) highlighted that utilising waste to produce bioenergy serves as an effective approach for both managing waste and recovering energy. This abundant biomass resource provides a promising basis for sustainable hydrogen production in the country. Utilising biomass waste for hydrogen could simultaneously manage agricultural waste and produce clean fuel, supporting Malaysia's transition goals from fossil fuels

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towards cleaner energy by reducing greenhouse gas emissions (GHG) (Rashidi et al., 2022). The Malaysian government has recognised this potential with the launch of a Hydrogen Economy and Technology Roadmap (HETR) in 2023 to promote hydrogen as a key energy carrier, including hydrogen derived from renewable sources like biomass (MOSTI, 2023).

As of 2024, Malaysia has not yet established any fully operational, commercial-scale hydrogen plants based on biomass waste. Nonetheless, several feasibility assessments and pilot initiatives are underway across the country. In particular, Sarawak has emerged as a frontrunner in hydrogen development with its ongoing hydrogen bus project and its broader ambition to become a regional green hydrogen hub. The state is progressing with key projects such as the Sarawak H2 Hub, H2ornbill, and H2biscus, aimed at producing and eventually exporting green hydrogen. Meanwhile, states like Johor and Sabah, which have a high density of palm oil mills, are increasingly being recognised as promising locations for decentralised hydrogen production, especially using POME as a feedstock. These regions offer both biomass resources and relatively well-developed infrastructure, making them suitable for pilot-scale implementations and scale-up. Biomass waste-based hydrogen offers a key advantage over other renewable pathways by enabling fossil-free hydrogen production, especially in regions with abundant biomass. Unlike electrolysis, biomass gasification can achieve net-negative emissions when integrated with carbon capture and storage (CCS), making it a strong complement in low-carbon energy strategies.

This review provides an overview of biomass waste-based hydrogen production availability in Malaysia. It begins with reviewing the major biomass feedstocks available in Malaysia for the hydrogen production. Next, it discusses the technologies which are thermochemical and biochemical technologies for converting these feedstocks into hydrogen fuel. Finally, it outlines the challenges and opportunities specific to Malaysia, and proposes future directions and research needs to harness biomass waste for hydrogen at scale. This review aims to inform researchers, policymakers, and industry stakeholders on the road ahead for biomass waste-derived hydrogen in Malaysia which aligns with global trends prioritising low-carbon hydrogen production to meet climate targets and energy needs.

2. Biomass Waste Sources for Hydrogen Production in Malaysia

Malaysia is richly endowed with biomass resources, particularly from its extensive palm oil industry, which spans over 5 Mha. Several by-products from palm oil processing are suitable for biohydrogen generation (Mohammed et al., 2011). Other main biomass wastes in Malaysia include rice husks, rice straw and sugarcane bagasse. Among these, oil palm residues are the most prominent due to the industry's scale where palm oil mills contribute to 95,814,456 t of feedstocks in 2022 (KPK, 2023). While often underutilised or used in low-value applications, these wastes are rich in carbon and hydrogen. Studies show that Malaysia has a large reserve of untapped biomass, offering significant potential for domestic hydrogen production from renewable sources (Teh et al., 2021). Table 1 summarises the biomass key feedstocks in Malaysia and its estimated quantities in 2022 based on Malaysia National Biomass Action Plan 2023-2030.

Table 1: Biomass waste feedstocks in Malaysia and its estimated annual quantity in 2022 (KPK, 2023)

Feedstocks	Estimated annual Quantity in 2022 (t)	Key Characteristics
Oil palm empty fruit bunch (EFB)	7,300,713	Lignocellulosic and bulky
Oil palm kernel shell (PKS)	4,425,176	Hard woody shell and high carbon content.
Palm oil mill effluent (POME)	63,525,686	High COD liquid waste and high organic loads.
Rice husk	534,356	Lignocellulosic and high silica content.
Rice straw	1,307,315	Lignocellulosic, high cellulose, and low density.
Sugarcane bagasse	7,510	Lignocellulosic and moist fibrous residue.

2.1 Oil palm residues

The palm oil sector is Malaysia’s largest contributor of biomass waste and forms the backbone of the country’s biohydrogen potential. Every year, Malaysia processes more than 20 Mt of crude palm oil, making it the world’s second-largest producer, resulting in around 1.07 t of empty fruit bunches (EFB) for every t of oil produced which results in more than 7 Mt of EFB each year (KPK, 2023). These residues are predominantly generated in palm oil-producing states such as Sabah, Sarawak, Johor, and Selangor, where the majority of Malaysia’s palm oil mills are concentrated.

Additional residues include mesocarp fibre, oil palm fronds, PKS and trunks, as well as liquid waste streams such as POME. These wastes are rich in lignocellulosic components such as cellulose, hemicellulose, and lignin, making them highly suitable for thermochemical conversion processes like gasification and pyrolysis to produce hydrogen-rich syngas (Hosseini et al., 2015). POME which has high organic load is widely available in

Malaysia and has been the subject of extensive research for biological hydrogen production via dark fermentation process (Ong et al., 2021).
According to Ruya et al. (2020), at a 15 wt% biomass concentration using empty fruit bunches, the use of a steam methane reformer led to a lower net hydrogen production because of the high percentage of the product gas being used as fuel (Ruya et al., 2020). However, when the biomass concentration was increased to 25 wt% using a combination of EFB and POME (Ruya et al., 2020), the net hydrogen yield rose significantly by up to 98 % (Ruya et al., 2020). Under optimal conditions, the process achieved an energy efficiency of 70 % without the reformer and 58.3 % with the reformer at the higher biomass concentration (Ruya et al., 2020).
Biomass waste-based hydrogen generation from POME and EFB using gasification, dark fermentation, and other treatment methods has shown significant potential for sustainable hydrogen production at the pilot scale in Malaysia (Ministry of Economy, 2023). Based on the National Energy Transition Roadmap (NETR), producing 1 kg of hydrogen requires 30 to 40 kg of EFB or 4 to 5 t of POME which shows Malaysia's strong potential for hydrogen production by biomass gasification (Ministry of Economy, 2023). The diversity and absolute volume of oil palm residues, both solid and liquid make this sector a cornerstone of Malaysia's biomass-based hydrogen strategy.

2.2 Rice husk

Rice cultivation generates another significant biomass stream for hydrogen production, particularly in Malaysia's northern and central states. On average, rice milling operations produce about 200 kg of rice husk for every t of paddy processed (Wan-Mohtar et al., 2023). With national paddy production ranging from 2 to 3 Mt annually, Malaysia produces nearly 534,356 t of rice husk each year, a by-product which rich in silica and carbon, making it suitable for thermochemical conversion (Kong et al., 2024). While this is limited in comparison to palm-based biomass, rice husk contains a high amount of silica and carbon, giving it significant potential and making it ideal for thermochemical processes like gasification or co-gasification with other feedstocks to generate (Wan Ab Karim Ghani et al., 2009). Additionally, the Malaysian government has categorised rice husk as a renewable resource and seeks to promote its transformation into valuable products, which may include hydrogen generation via thermochemical methods (SEDA, 2021).

2.3 Rice straw

Rice straw is an important but underutilised agricultural residue in Malaysia, particularly prevalent in major rice-producing states such as Kedah, Perlis, and Selangor. It refers to the stems or stalks left over after the rice grains are harvested. After harvesting, rice straw is often left to decompose or openly burned in fields (Gonocruz et al., 2024), contributing to haze and greenhouse gas emissions, positioning it among the top contributors of lignocellulosic waste worldwide (Morya et al., 2023). Given its lignocellulosic nature which rich in cellulose, hemicellulose, and lignin same like palm oil, it holds great potential as a feedstock for hydrogen production via thermochemical routes like gasification (Singh et al., 2025). However, the reliable and seasonal presence of rice straw makes it a suitable feedstock for decentralised hydrogen systems in rural Malaysia.

2.4 Sugarcane bagasse

The fibrous material left over after extracting juice from sugarcanes is an underutilised biomass source for hydrogen production in Malaysia. While sugarcane is not as extensively grown as oil palm or rice, its plantations still produce about 25,118 t of cane each year, resulting in an approximate yield of 7,510 t of bagasse in 2022 (KPK, 2023). Bagasse is primarily composed of cellulose and hemicellulose, lending itself well to both gasification and biochemical conversion processes. Research has shown that gasification of sugarcane bagasse can yield up to 100 kg of hydrogen per t of dry feedstock under optimal conditions, depending on gasifier configuration and catalysts used (Raheem et al., 2019). In Malaysia, sugar mills are commonly equipped with boilers that burn bagasse for heat, however integrating hydrogen production units could enhance resource utilisation and value-added energy pathway. The seasonal nature and localised production of bagasse make it suitable for decentralised hydrogen systems, particularly when co-processed with other agricultural residues such as oil palm biomass or rice husk (Abogunrin-Olafisoye et al., 2024).

3. Hydrogen production technologies in Malaysia

3.1 Biochemical conversion

Dark fermentation is a common biochemical pathway in Malaysia, especially for wet biomass like POME, food waste, agricultural residues (after suitable pre-treatment). "Dark" means it does not require light, distinguishing it from photo-fermentation. Malaysia has seen some research in dark fermentation for hydrogen, particularly using POME and palm biomass hydrolysates as POME is readily available at palm oil mills and contains high concentrations of degradable sugars, proteins, and lipids.

Microbial digestion under anaerobic conditions generates hydrogen and volatile fatty acids. Photo-fermentation, though still in early research stages, uses photosynthetic bacteria to convert organic acids (from dark fermentation) into additional hydrogen under light (Mustapha et al., 2025). The tropical climate of Malaysia offers favourable conditions for such systems.

3.2 Thermochemical conversion

In Malaysia, thermochemical processes such as pyrolysis and gasification have been widely studied for converting solid biomass into hydrogen-rich syngas. Figure 1 shows the pathway of hydrogen production by thermochemical process from biomass waste collection, the treatment until the production of hydrogen.
Gasification operates under limited oxygen condition at a high temperature typically between 700°C to 1000°C (Obiora et al., 2024), often using steam to enhance hydrogen yield. Studies on PKS and EFB gasification have shown hydrogen content are high in syngas (Barco-Burgos et al., 2021). In addition, supercritical water gasification (SCWG) offers an efficient pathway to convert wet biomass like POME into hydrogen-rich syngas without the need for energy-intensive drying, making it ideal for high-moisture feedstocks.
Pyrolysis, typically operated at lower temperatures (400–600°C) with 1 to 5 bars of pressure (Demirbaş, 2001), produces bio-oil and syngas. When coupled with vapor reforming, pyrolysis products can be further processed to extract hydrogen. Although pyrolysis alone yields limited hydrogen, its integration into modular systems offers flexibility for smaller operations, especially at palm oil mills (Gonocruz et al., 2024).
Among the various technology pathways under consideration, co-gasification has emerge as a promising option for integrating biomass into Malaysia's existing energy infrastructure before Malaysia switched to a cleaner production (Ram and Mondal, 2022). Co-gasification of oil palm biomass with coal and other waste residues is technically possible and feasible in Perak, Selangor, and Johor, where legacy biomass and coal facilities already exist. These states also have supporting infrastructure, trained workforce, and grid connectivity to integrate hydrogen as a co-product while Sabah and Sarawak, with abundant biomass, require additional logistics and grid development for co-gasification feasibility.

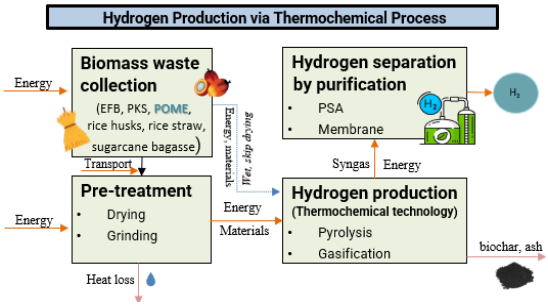

Figure 1: Hydrogen production via thermochemical process

4. Policy Implementation and Strategies

The development of Malaysia's biomass-based hydrogen production requires strong policy execution between ministries, efficient public–private stakeholder partnerships, and incentives to spur technological innovation, financial incentives, domestic production, and green workforce development.
The use of biomass wastes for hydrogen production is in harmony with a variety of goals such as better waste management, cleaner energy, and rural development. Integration of hydrogen facilities at palm oil mills can mitigate disposal issues while enhancing the availability of energy where it is required. More pilot projects and studies on co-gasification, modular designs, and mixed waste streams can intensify these efforts. According to Chelvam et al. (2025), shifting to low-carbon hydrogen relies on supportive policies involving financial incentives, partnerships, regulations, and ongoing research and development (R&D). Learning from positive global case studies also helps to inform the creation of effective hydrogen strategies. To move forward, Malaysia needs clear support mechanisms on mapping biomass resources for centralised and decentralised for logistics, feedstock standardisation, and incentivising waste-to-energy projects in target sectors. International collaborations such as Japan-Malaysia Clean Energy Partnership could also channel technology transfer and capital for Malaysia. Technical roadmaps and R&D on low-cost, locally suitable technologies are also needed. Such steps can expedite hydrogen rollout and serve multiple end users.
Malaysia's policy environment is increasingly supportive of such transitions. The National Energy Transition Roadmap (NETR) identifies hydrogen as a key part of Malaysia's clean energy strategy (Ministry of Economy, 2023). The Hydrogen Economy and Technology Roadmap (HETR) explicitly highlight hydrogen, including from biomass, as a future energy vector (MOSTI, 2023). These frameworks align with Malaysia's Nationally Determined Contributions (NDCs), which outline its commitment to achieving net-zero emissions by 2050 and

the updated National Biomass Action Plan 2023-2030 promotes the use of biomass as a catalyst for green growth (KPK, 2023).Referring to HETR, Malaysia has set ambitious targets to become a major hydrogen producer in the region, with planned output reaching up to 2 Mt annually by 2030, and 16 Mt by 2050 under an Emission-Driven Scenario (MOSTI, 2023). This transition could generate more than MYR 905 billion in revenue by 2050. From a biomass waste perspective, Malaysia produces over 90 M dry t of oil palm waste each year (MIDA, 2024). Given a typical hydrogen yield approximately 100 kg per t via gasification (Chang et al., 2011), the country holds the potential to generate approximately 9 Mt of hydrogen annually from biomass alone.
To ensure widespread adoption, policymakers are encouraged to scale up research, pilot, and demonstration projects focusing on modular gasification units, co-gasification of agricultural and plantation waste, and dark fermentation of wet organic streams such as POME. These efforts should also be aligned with circular economy principles, ensuring resource efficiency and promoting localised hydrogen ecosystems.

5. Conclusions

Malaysia's abundant biomass resources in the form of oil palm residues, rice husk, rice straw, and sugarcane bagasse make an excellent feedstock for hydrogen production in Malaysia. Thermochemical processes consisting of pyrolysis and gasification are extremely well adapted to lignocellulosic waste residues, whereas biochemical processes comprising dark fermentation have the potential to process wet biomass like POME. By synchronising technological advancement with facilitating policies and making use of the current agro-industrial ecosystem, Malaysia has the potential to convert its biomass wastes into a significant component of its hydrogen economy. Future developments must focus on demonstration projects, develop modularised technologies, and consolidate the value chain of biomass. This review highlights the strategic alignment between biomass utilisation and Malaysia’s hydrogen policy ambitions. However, this study focused solely on biomass-based hydrogen and does not include detailed techno-economic analysis or comparative assessments with other renewable hydrogen pathways such as electrolysis or solar source. These limitations, particularly on the economic feasibility should be addressed in future research to support comprehensive decision-making. Overall, leveraging local biomass through targeted technologies can position Malaysia as a key player in the regional green hydrogen landscape.

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