Toward a Sustainable Energy Future: Agricultural Waste as a Bioenergy Resource in Malaysia

Siti Norliyana Harun[a*], Azwani Alias[b] & Kiman Siregar[c]

[a]*Centre for Tropical Climate Change System, The University of Malaysia, Bangi, Selangor, Malaysia*
[b]*Faculty of Allied Health Science, City University Malaysia, Jalan teknokrat 3, Cyber 4, 63000 Cyberjaya, Selangor, Malaysia*
[c]*Dakara Bisnis Institute, Jl. Lingkar Baru laladon Dramaga IPB Bogor No. 9, Babakan, Kec. Dramaga, Jawa Barat 16680, Indonesia*
**Corresponding author: sitinorliyana@ukm.edu.my*

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ABSTRACT

Malaysia's agricultural sector generates extensive amounts of biomass waste annually, primarily from palm oil, rice, rubber, and coconut production. This biomass waste, largely disposed of through environmentally harmful practices such as open burning and landfilling, represents a significant untapped resource for renewable energy production. Converting agricultural waste into bioenergy offers a sustainable pathway for Malaysia to achieve its renewable energy goals, mitigate greenhouse gas (GHG) emissions, and support rural economic development. This review examines Malaysia's current capacity and readiness to utilize agricultural waste for bioenergy, assessing existing waste resources, predominant waste management practices, and major barriers to bioenergy adoption. Key challenges identified include high initial capital costs, limited technical expertise, regulatory complexities, and low public awareness, which collectively hinder the scalability of bioenergy solutions. To address these challenges, the review proposes several targeted strategies, including the adoption of advanced bioenergy technologies such as anaerobic digestion, biomass pelletization, and biochar production; the establishment of supportive policy measures like bioenergy-specific subsidies and carbon pricing; and the promotion of public-private partnerships and community engagement initiatives. Through these interventions, Malaysia can effectively leverage its agricultural biomass resources, contributing to its energy independence and environmental sustainability goals. This paper underscores the potential of bioenergy from agricultural waste as a viable renewable energy solution, providing a pathway for Malaysia to align its economic and environmental objectives.

Keywords: Waste management; Renewable energy; Sustainability; Climate action; Recycling

1. INTRODUCTION

The extensive reliance on fossil fuels to meet global energy demands has led to critical environmental issues, particularly concerning greenhouse gas (GHG) emissions. Consequently, these emissions significantly contribute to global warming and climate change. Like many other nations, there is a pressing need in Malaysia to reduce its environmental footprint while meeting rising energy demands. Therefore, Malaysia aims to lowering its GHG emission intensity per unit of Gross Domestic Product (GDP) by 45% by 2030 compared to 2005 levels (Harun et al., 2022). Additionally, the Malaysian government has pledged to achieve net-zero emissions by 2050, a target that necessitates a significant shift from fossil fuel dependence to sustainable energy sources. This target has accelerated the search for alternative energy sources, with biomass emerging as a promising solution due to its renewable nature, potential for low emissions, and extensive availability.

Biomass energy, derived from organic material such as agricultural residues and forestry by-products, offers numerous advantages in the Malaysian context. Biomass offers a sustainable and carbon-neutral alternative to conventional fuels and has the potential to address multiple critical issues beyond just energy production. Malaysia's agricultural sector, which includes extensive palm oil, rice, and rubber industries, generates a substantial volume of waste annually. This agricultural waste, comprising materials such as palm oil mill effluent (POME), empty fruit bunches (EFB), rice husks, and rubberwood residues, is readily available and could serve as a valuable feedstock for bioenergy production. Transforming this waste into energy could reduce reliance on fossil fuels, enhance energy security, and mitigate environmental impacts associated with improper waste disposal., Additionally, bioenergy has the potential to support rural economic development by creating new income streams for agricultural communities and reducing the environmental burdens of traditional waste management practices.

The benefits of bioenergy are evident in its potential to reduce GHG emissions, promote energy independence, and contribute to Malaysia's renewable energy targets. Compared to fossil fuels, the combustion or processing of biomass emits fewer pollutants, making it a cleaner alternative that could significantly lower Malaysia's carbon footprint. The adoption of bioenergy could play a substantial role in strengthening Malaysia's renewable energy sector, thereby aligning with the country's commitments to international climate agreements such as the Paris Agreement (Rashidi et al., 2022). Furthermore, effective utilization of biomass would help alleviate waste management issues by diverting agricultural residues from environmentally detrimental disposal methods like open burning and landfilling.

Despite the advantages, there are still several obstacles in Malaysia's path to fully implementing agricultural waste as a primary energy source. While government initiatives such as renewable energy policies, incentives, and the Feed-in Tariff (FiT) program, have aimed to promote bioenergy, the sector has struggled to achieve significant market penetration. Malaysia faces numerous barriers, including high initial capital expenditures, limited technical expertise, insufficient financial support, and low public awareness. Additionally, policy measures like carbon taxes and pricing have not yet gained robust support in many Asian countries, including Malaysia, which limits industry enthusiasm for renewable energy projects, including bioenergy (Rashidi et al., 2022). Moreover, concerns related to deforestation, potential GHG emissions from biomass processing, and the complexity of biomass supply chains pose further environmental and logistical challenges. Given these obstacles, it is essential to understand the current state, challenges, and limitations of biomass waste valorization for bioenergy in Malaysia.

This paper aims to provide a brief review of Malaysia's readiness to utilize agricultural waste for bioenergy production. It examines the country's existing agricultural waste resources, current waste management practices, the primary challenges hindering bioenergy adoption, and proposing potential strategies for sustainable biomass utilization in the future. By identifying these bottlenecks, this review seeks to provide strategic recommendations for policymakers and stakeholders to effectively leverage Malaysia's biomass resources and ensure that agricultural waste can be sustainably transformed into a viable energy source. In doing so, this paper contributes to the broader discourse on renewable energy in Malaysia and underscores the potential of bioenergy as a sustainable pathway toward meeting the nation's environmental and economic objectives.

2. AGRICULTURAL WASTE IN MALAYSIA

Malaysia's agricultural sector, one of the largest in Southeast Asia, is highly productive and diverse, encompassing major crops such as oil palm, rice, rubber, and coconut. These agricultural activities generate significant quantities of organic residues, collectively referred to as agricultural waste or biomass. Despite the substantial volume of waste produced, much of it remains underutilized and is commonly disposed of through methods such as open burning and landfill, which are environmentally harmful. By rethinking the management of these residues, Malaysia can convert this waste into valuable bioenergy, aligning with its renewable energy and environmental sustainability targets.

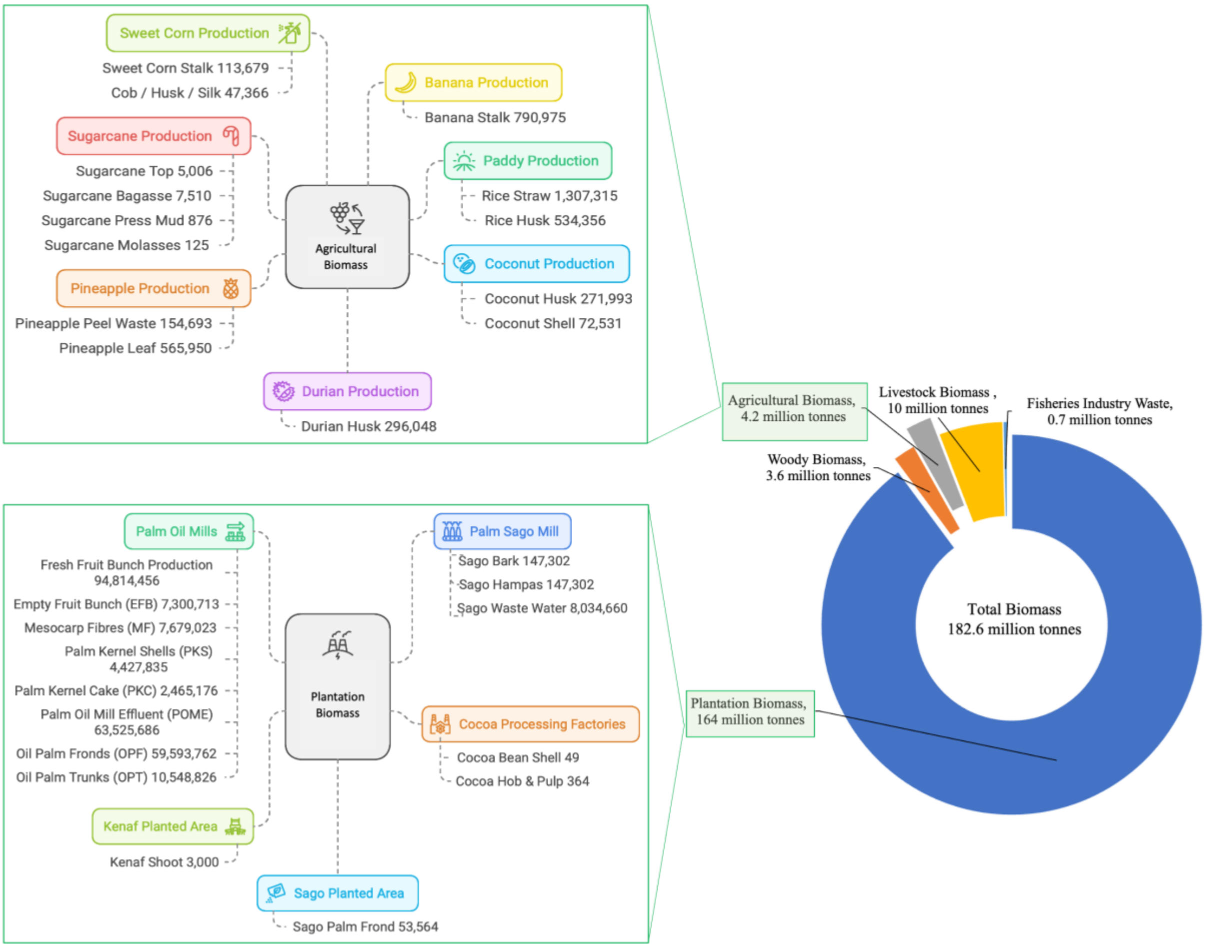
2.1 Types of Agricultural Waste and Bioenergy Potential

Malaysia's agricultural sector is highly diverse, encompassing large-scale production of palm oil, rice, rubber, and various fruits, which collectively generate substantial quantities of agricultural waste. This biomass, often referred to as agricultural waste, is abundant but remains largely underutilized. With the country positioned as one of Southeast Asia's major agricultural producers, Malaysia has an immense supply of biomass waste that could be repurposed for bioenergy production. Despite this potential, much of this waste is currently disposed of through traditional methods that are often harmful to the environment.

Agricultural waste in Malaysia comes from a wide range of organic materials, mainly from crop production, post-harvest residues, and processing by-products. A significant portion of this waste comes from the palm oil industry, which is among the largest agricultural contributors in the country. Major by-products from palm oil processing include POME, EFB, palm kernel shells (PKS), and mesocarp fiber (MF). Each of these by-products has bioenergy potential; for example, POME, a high-organic liquid waste, can be used to produce methane-rich biogas, while EFB and palm kernel shells have high calorific values, making them suitable for direct combustion and other bioenergy processes. In addition to palm oil waste, rice residues, such as rice husks and straw, form another major category of biomass. Rice husks are the hard outer shells separated during milling, while rice straw comprises stems and leaves left in the fields after harvest. Both residues have bioenergy potential and are found in large quantities in rice-producing regions like Kedah and Selangor.

Malaysia's agricultural sector also produces a range of other biomass residues with significant potential for energy generation. Rubberwood residues, generated during tree pruning and replanting cycles, have a calorific value of 17–18 MJ/kg, making them suitable for combustion, gasification, or co-firing with coal (Kasawapat et al. 2024). Similarly, coconut shells and husks, with a calorific value of 12–20 MJ/kg, are highly suitable for biochar production, combustion, or small-scale pyrolysis, particularly for rural energy applications (Harun et al. 2020). Sugarcane bagasse, a fibrous by-product of juice extraction, is commonly utilized for combined heat and power (CHP) generation in sugar mills, reducing reliance on external fuel sources. Palm oil trunk (POT), often overlooked, is generated during replanting cycles and offers significant bioenergy potential through pyrolysis or advanced gasification technologies. Wood waste, produced as a by-product of forestry operations and furniture manufacturing, has substantial potential for combustion or gasification to generate heat and power. Finally, rubber seeds, known for their high oil content, are a promising feedstock for bio-oil extraction or biodiesel production.

The volume of agricultural waste generated in Malaysia each year is substantial, with an estimated 168 million tonnes of biomass waste produced annually. According to Malaysia's National Biomass Action Plan 2023-2030, agricultural biomass contributed a total of 89.8% (164 million tonnes) and agricultural biomass contributed 2.3% (3.6 million tonnes) of total biomass in 2022 (Figure 1). The palm oil sector alone contributes approximately 100 million dry tonnes of this total, including 60 million tonnes of POME and around 20 million tonnes of EFB. With over 450 palm oil mills in Malaysia, particularly in high-production areas such as Sabah, Sarawak, Johor, and Pahang, the volume of waste generated by the industry is both significant and regionally concentrated. Rice cultivation also contributes significantly to Malaysia's biomass waste, producing around 700,000 tonnes of rice husk and straw annually (Kaita et al., 2023). These residues are often found in the northern rice-growing regions, where they are typically left in fields or transported to nearby mills. The rubber and coconut industries, although smaller, also contribute notable amounts of biomass waste. Coconut shells and husks alone account for approximately 500,000 tonnes of waste per year, while rubber plantations yield additional waste from pruning and replanting activities. Smaller quantities of biomass are generated by other agricultural activities, such as sugarcane production, which yields bagasse, and fruit farming, which produces seasonal organic waste.



*Unit = tonnes

Figure 1. Malaysia's agricultural biomass generated in year 2022.
Source: Malaysia's National Biomass Action Plan 2023-2030

2.2 Agricultural Waste Management Practices

Current waste management practices in Malaysia rely heavily on conventional and often environmentally detrimental methods. Open burning is widely used to dispose of agricultural waste, particularly rice straw and other crop residues left in fields after harvest. This practice, though low-cost and effective for clearing fields, releases substantial amounts of carbon dioxide, methane, and particulate matter into the atmosphere, contributing to air pollution and impacting respiratory health in surrounding communities. In some cases, agricultural waste that cannot be burned is simply discarded in landfills or left to decompose on-site. While landfilling prevents immediate environmental hazards, it leads to the production of methane through the anaerobic decomposition of organic material . Additionally, leachate from decomposing biomass in landfills poses a risk of contaminating soil and groundwater. In certain instances, agricultural residues such as EFB and rice straw are used as soil amendments to improve fertility and prevent erosion. While this practice can enhance soil health by recycling nutrients, it also has limitations. The high carbon-to-nitrogen ratio of some residues can lead to nitrogen immobilization, which inhibits plant growth, while others, like EFB, decompose slowly, potentially obstructing plant root development (Pulingan et al., 2022).

Given the large quantities of agricultural waste produced each year and the associated environmental impacts of current practices, it is crucial for Malaysia to adopt sustainable waste valorization methods. Converting agricultural waste to bioenergy offers a viable alternative, aligning with Malaysia's renewable energy goals and reducing the ecological footprint of agricultural activities. By diverting biomass from open burning and landfill, bioenergy initiatives can significantly lower emissions, promote rural economic development, and enhance energy security. As Malaysia strives to achieve its carbon reduction commitments, transitioning to bioenergy through effective waste valorization is both timely and necessary. This transition will require support from government policies, investment in bioenergy technologies, and active engagement with rural communities and industries to establish sustainable and scalable waste-to-energy solutions.

3. BIOENERGY POTENTIAL OF AGRICULTURAL WASTE IN MALAYSIA AND ITS SUITABLE CONVERSION TECHNOLOGIES

Malaysia's agricultural sector generates a substantial amount of biomass waste annually, offering significant potential for bioenergy applications. Transforming this waste into bioenergy could provide a renewable, sustainable source of energy that addresses Malaysia's dual challenges of waste management and energy security. This section examines the bioenergy potential of different types of agricultural waste in Malaysia, exploring suitable conversion technologies and their environmental benefits. Table 1 summarizes the bioenergy applications, suitable bioenergy conversion technologies, and associated benefits of key agricultural wastes in Malaysia.

Table 1. Bioenergy Potential of Major Agricultural Waste Types in Malaysia.

Agricultural Waste Type	Description & Characteristics	Energy Potential	Suitable Bioenergy Technologies	Environmental & Economic Benefits
Palm Oil Mill Effluent (POME)	Liquid waste from palm oil extraction; high organic content.	Methane-rich biogas production (up to 65% methane content) (Shukla et al., 2024; Amin et al., 2022; Aziz et al., 2020).	Anaerobic Digestion (AD)	- Reduces open dumping and methane emissions. - Generates renewable biogas for power and heat. - Supports circular economy by converting waste to energy.
Empty Fruit Bunches (EFB)	Solid, fibrous residue from oil palm fruit processing. Calorific value: ~18 MJ/kg (Helwani et al., 2018; Nyakuma et al., 2014).	High energy yield through direct combustion or pyrolysis.	Combustion, Gasification, Pyrolysis	- Reduces reliance on fossil fuels through biomass energy. - Minimizes waste accumulation at mills. - Avoids air pollution from open burning of EFBs.
Palm Kernel Shells & Mesocarp Fiber	Hard, fibrous by-products; palm kernel shells have lower moisture and are easier to transport. Calorific value: ~18-20 MJ/kg (Rahim et al., 2023; Ordoñez-Frías et al., 2020; Sukiran et al., 2017).	Efficient in CHP systems, industrial boilers, and co-firing with coal.,	Combustion, Co-firing	- Provides high-quality fuel for industrial boilers. - Contributes to local energy security by utilizing in-mill residues. - Decreases fossil fuel dependency in

Agricultural Waste Type	Description & Characteristics	Energy Potential	Suitable Bioenergy Technologies	Environmental & Economic Benefits
				industrial applications.
Rice Husk	Hard outer shell separated from rice grain during milling. Calorific value: ~15 MJ/kg (Firdaus et al., 2024; Dafiqurrohman et al., 2022).	Suitable for electricity generation in rural areas.	Combustion, Gasification	- Reduces need for open burning, minimizing air pollution. - Supports rural electrification through decentralized power generation.
Rice Straw	Stems and leaves left after rice harvest; high cellulose content, suitable for bioethanol. Calorific value: ~12-14 MJ/kg (Firdaus et al., 2024; Alengebawy et al., 2023: Harun et al., 2022).	Can be converted to bioethanol or biogas.	Combustion, Gasification, Anaerobic Digestion, Bioethanol Production	- Reduces open burning of crop residues, lowering emissions. - Provides alternative fuel sources (e.g., bioethanol). - Encourages value-added utilization of rice farming residues.
Rubberwood Residues	Waste wood from rubber tree pruning and end-of-lifecycle tree removal., Calorific value: ~17-18 MJ/kg (Quartey et al., 2022; Ali et l. 2021).	Provides stable supply for heat and power.	Combustion, Gasification, Co-firing	- Supports sustainable energy by replacing fossil fuels. - Reduces waste from rubber plantations. - Potential for co-firing to reduce fossil fuel consumption.
Coconut Shells & Husks	Hard shells and husks generated during coconut processing; high energy density. Calorific value: ~12-20 MJ/kg (Ahmad et al., 2022; Tanko et al., 2021; Saharudin et al., 2024).	Useful for biochar production and small-scale energy applications.	Combustion, Biochar Production, Pyrolysis	- Supports rural bioenergy and biochar production. - Creates a high-energy biofuel suitable for small-scale applications.
Sugarcane Bagasse	Fibrous residue left after juice extraction from sugarcane. Calorific value: ~17 MJ/kg (Stegen & Kaparaju 2020; Ozturk et al., 2017).	Commonly used in sugar mills for combined heat and power.	Combustion, Gasification	- Provides energy source within sugar industry, reducing external fuel needs. - Minimizes waste management issues

Agricultural Waste Type	Description & Characteristics	Energy Potential	Suitable Bioenergy Technologies	Environmental & Economic Benefits
				related to bagasse disposal.
Fruit and Vegetable Waste	Seasonal, diverse organic residues from crops like banana, pineapple, and vegetables.	Biogas production potential, suitable for decentralized energy systems.	Anaerobic Digestion	- Reduces organic waste in landfills, lowering methane emissions. - Supports decentralized bioenergy in rural areas. - Provides renewable energy for small farms and communities.

a. Palm Oil Mill Effluent (POME)

Palm oil mill effluent (POME) is a high-organic liquid by-product generated during the extraction of palm oil. Due to its rich organic content, POME is particularly suitable for conversion through anaerobic digestion (AD). AD processes POME in an oxygen-free environment, producing methane-rich biogas that can be used for heat and power generation. Biogas from AD has a methane content of up to 65%, providing a substantial energy source while also addressing waste management issues in the palm oil industry (Shukla et al., 2024). In addition to biogas, AD produces nutrient-rich digestate, which can be applied as a soil amendment, supporting agricultural sustainability and promoting a circular economy. The methane capture aspect of AD is crucial, as it prevents the release of a potent greenhouse gas into the atmosphere, thus aligning with Malaysia's climate commitments (Harun et al., 2022).

b. Empty Fruit Bunches

Empty fruit bunches (EFB) has a high calorific value of approximately 18 MJ/kg, making it an excellent feedstock for combustion, gasification, and pyrolysis Helwani et al., 2018; Nyakuma et al., 2014). Combustion of EFB is widely practiced for direct heat generation, often in industrial boilers. In contrast, gasification of EFB under limited oxygen conditions produces syngas, a versatile fuel for electricity generation. Pyrolysis, which involves heating EFB in an oxygen-free environment, converts it into bio-oil, biochar, and syngas. The bio-oil can be refined into liquid fuel, while biochar offers environmental benefits through soil conditioning and carbon sequestration, making it an invaluable negative-emissions technologi. Utilizing EFB for bioenergy production reduces dependency on fossil fuels, minimizes waste accumulation at processing facilities, and provides a cleaner alternative to open burning, which remains prevalent in many rural areas.

c. Rice Husk and Rice Straw

Rice husks and straw are significant by-products of rice cultivation in Malaysia. Rice husk, the hard outer shell separated during milling, and rice straw, the stalk left after harvest, have substantial energy potential., These residues can be utilized through combustion, gasification, anaerobic digestion, and bioethanol production. Combustion of rice husk provides decentralized power in rural areas, supporting local energy needs and reducing open burning practices. Gasification, particularly suited for rice husk, generates syngas that can be used for electricity and industrial applications (Firdaus et al., 2024; Dafiqurrohman et al., 2022). Additionally, rice straw has potential for bioethanol production, a valuable biofuel alternative to gasoline. Transitioning to these bioenergy solutions promotes sustainable energy use in rice-growing regions and reduces the environmental impact associated with traditional disposal methods, such as open burning (Firdaus et al., 2024; Alengebawy et al., 2023: Harun et al., 2022).

d. Rubberwood Residues

Rubber plantations produce significant waste in the form of rubberwood residues, particularly during tree replanting and pruning cycles. With a calorific value of 17-18 MJ/kg, rubberwood is an efficient biomass for combustion, gasification, and co-firing with coal (Quartey et al., 2022; Ali et l. 2021). Combustion of rubberwood residues in industrial boilers provides a renewable source of heat and power, while gasification produces syngas, which can replace fossil fuels in various applications (Sultan et al., 2021). The use of rubberwood for bioenergy aligns with sustainable forestry practices and reduces the environmental footprint associated with rubber production. Utilizing this biomass further supports Malaysia's energy independence by providing an alternative to imported fossil fuels, which stabilizes energy costs and strengthens energy security.

e. Coconut Shells and Husks

Coconut shells and husks is generated during coconut processing. It is rich in lignocellulosic material and have a high energy density (~12-20 MJ/kg), making them suitable for biochar production, combustion, and small-scale pyrolysis. Biochar produced from coconut shells can be used to enhance soil quality, particularly in nutrient-poor soils, while also sequestering carbon, thus mitigating climate change effects (Saharudin et al.,2024). In addition, the high calorific value of coconut shells supports their use as a high-energy biofuel, especially in regions with decentralized energy needs. Utilizing these residues for bioenergy contributes to rural development and supports sustainable agricultural practices, providing a valuable fuel source and reducing waste (Su et al., 2022).

f. Sugarcane Bagasse

Bagasse is the fibrous residue left after juice extraction from sugarcane. It is commonly used in sugar mills for combined heat and power (CHP) generation. This approach reduces external energy needs within the sugar industry by providing a renewable energy source from within the production process. Bagasse has a calorific value of approximately 17 MJ/kg, making it an efficient fuel for CHP applications (Stegen & Kaparaju 2020; Ozturk et al., 2017). The conversion of bagasse into bioenergy not only supports waste reduction but also contributes to sustainable energy practices within the industry, reducing reliance on fossil fuels and lowering operational costs.

g. Fruit and Vegetable Waste

Seasonal agricultural waste from fruits and vegetables, including residues from crops like bananas, pineapples, and various vegetables, can be converted into biogas through anaerobic digestion. This technology is particularly useful in decentralized bioenergy systems, as it allows rural areas to process organic waste locally, producing renewable energy for small farms and communities. AD of fruit and vegetable waste reduces landfill use and methane emissions, supporting environmental sustainability and contributing to Malaysia's renewable energy landscape (Ozturk et al., 2017).

3.1 Environmental and Economic Benefits of Bioenergy

The bioenergy potential of Malaysia’s agricultural waste extends beyond energy production, offering significant environmental and economic benefits that align with the country’s sustainability objectives. Transitioning from conventional waste disposal methods to bioenergy mitigates various environmental issues, particularly air pollution. Open burning releases harmful pollutants, including carbon monoxide, methane, and particulate matter, which pose health risks to surrounding communities. By converting agricultural waste into bioenergy, these pollutants are significantly reduced, supporting cleaner air and improved public health. Bioenergy technologies such as anaerobic digestion and pyrolysis capture greenhouse gases like methane and carbon during conversion, preventing their release into the atmosphere. For instance, AD of POME captures methane, repurposing it as renewable fuel and reducing Malaysia’s greenhouse gas emissions footprint (Shukla et al., 2024). Additionally, biochar production from pyrolysis sequesters carbon in a stable form, enhancing soil quality while contributing to negative emissions, which supports Malaysia’s commitments to international climate agreements like the Paris Agreement (Saharudin & Jeswani, 2024).

Economically, bioenergy development provides new revenue streams for rural communities. By selling agricultural residues for bioenergy, farmers diversify their income sources, which fosters economic resilience in rural areas and encourages sustainable waste management practices. Establishing bioenergy infrastructure, such as AD facilities and biomass pellet plants, also generates employment opportunities across construction, maintenance, and operations, stimulating local economies and strengthening Malaysia's renewable energy sector (Zailan et al., 2021; Rahim et al., 2023). Furthermore, bioenergy production from local agricultural waste reduces Malaysia's reliance on imported fossil fuels, enhancing energy security and stabilizing energy costs amidst global market volatility (Kamaruzaman et al., 2023).

Malaysia's agricultural waste presents vast potential for bioenergy production, with each waste type suited to specific conversion technologies that maximize both environmental and economic benefits. By investing in these technologies, Malaysia can establish a sustainable, circular bioeconomy, where agricultural waste is continuously recycled into productive uses, supporting national energy goals, rural development, and environmental sustainability.

4. CHALLENGES AND BARRIERS

The utilization of agricultural waste for bioenergy in Malaysia offers substantial potential to meet rising energy demands sustainably while managing agricultural residues that would otherwise go to waste. However, transforming these biomass resources into bioenergy faces numerous technical, economic, social, and policy-related challenges that limit the scalability and commercial viability of bioenergy projects. Recognizing and addressing these barriers is essential for Malaysia to fully realize the potential of agricultural waste as a renewable energy source. The following sections detail the key obstacles to bioenergy development in Malaysia.

4.1 Technical Challenges

One of the primary technical challenges facing the bioenergy sector in Malaysia is the limited technology readiness and scalability of bioenergy technologies. While technologies such as fermentation, anaerobic digestion, and gasification have demonstrated potential for converting agricultural waste into bioenergy, many are still in the pilot or laboratory stages in Malaysia. This lack of technological maturity limits the commercial application of bioenergy solutions, as transitioning from pilot projects to industrial-scale operations requires significant technological development, investment, and adaptation to local conditions (Umar et al., 2021; Lim et al., 2021). The complexity of scaling these technologies also raises costs and operational risks, deterring investors and stakeholders from committing to large-scale projects.

Feedstock variability is another significant technical barrier. The composition, moisture content, and calorific value of agricultural residues such as oil palm empty fruit bunches (EFB) and rice husks can vary significantly depending on the source, season, and handling practices. This inconsistency impacts the efficiency and effectiveness of bioenergy conversion processes, as many technologies are sensitive to feedstock quality (Mustafa et al., 2023; Albahnasawi et al., 2024). Variations in feedstock properties require constant adjustments to processing parameters, making it challenging to achieve stable energy yields and reliable bioenergy outputs. Additionally, optimizing conversion efficiency remains a hurdle. Technologies like anaerobic digestion and incineration, while promising, often struggle with low conversion efficiencies and environmental emissions management. Some processes may emit carcinogenic substances and other pollutants, requiring advanced emission control systems and adding to the overall cost and complexity of bioenergy production (Shukla et al., 2024; Raina et al., 2024).

4.2 Economic Barriers

Economic barriers play a substantial role in limiting the viability of bioenergy projects in Malaysia. Establishing bioenergy facilities entails high initial capital investment, encompassing costs related to plant construction, equipment acquisition, and technology deployment. These upfront costs are a major deterrent, especially for small- and medium-sized enterprises (SMEs) that may lack the financial capacity to invest in costly bioenergy infrastructure (Yow et al., 2024; How et al., 2019). Furthermore, the economic feasibility of bioenergy projects is often challenged by high operational costs, including feedstock collection, transportation, and maintenance, as well as the need for competitive pricing against fossil fuels. The lower cost of conventional fossil fuels in Malaysia makes it difficult for bioenergy to compete without substantial subsidies or price adjustments, making bioenergy projects less attractive from an economic perspective (Rashidi et al., 2022; Raina et al., 2024).

The uncertainty in the market for bioenergy products, such as biochar, biogas, and bioethanol, further complicates the economic landscape. The demand for these products remains inconsistent, and without established markets, bioenergy developers face challenges in securing stable revenue streams. Additionally, the absence of carbon pricing mechanisms or financial incentives for carbon reduction makes it challenging to capture the environmental value of bioenergy, thereby reducing its appeal to investors who prioritize short-term financial returns over long-term environmental benefits.

4.3 Social and Awareness Barriers

Social acceptance and public awareness are critical factors that influence the success of bioenergy initiatives in Malaysia. Currently, there is limited public understanding of bioenergy technologies, leading to misconceptions and a lack of acceptance. Many rural communities, where agricultural waste is abundant, are unfamiliar with the benefits and applications of bioenergy, which can hinder the adoption of bioenergy projects. The lack of awareness and misinformation may foster resistance to new technologies, as communities may have concerns about potential health and environmental impacts or may not fully understand the economic benefits that bioenergy could bring (How et al., 2019).

Community engagement is essential to foster social acceptance and ensure that local populations are receptive to bioenergy projects. However, varying levels of awareness and interest present challenges in effectively engaging communities and securing their support. To achieve broad acceptance, bioenergy developers and policymakers must invest in community outreach and educational programs to raise awareness about bioenergy's environmental and economic benefits. Without active community participation and support, bioenergy projects risk facing opposition, which can delay or obstruct implementation (Lim et al., 2021).

4.4 Policy and Regulatory Challenges

Policy and regulatory barriers pose significant challenges to the growth of Malaysia's bioenergy sector. Although the Malaysian government has introduced several renewable energy initiatives, the lack of comprehensive and consistent policy support for bioenergy hinders the sector's development. Current policies often do not provide specific incentives tailored to bioenergy or agricultural waste valorization, resulting in inconsistent support across different regions and industries. For instance, the Feed-in Tariff (FiT) program, which promotes renewable energy, has limited incentives specifically for bioenergy projects, making it challenging for bioenergy developers to secure sufficient financial support (Yow et al., 2024; Rashidi et al., 2022).

Regulatory complexity and the absence of clear guidelines for bioenergy project development further complicate the landscape. The bioenergy sector is regulated by multiple agencies, leading to overlapping responsibilities and delays in project approvals, licensing, and compliance processes. The lack of a centralized regulatory framework for bioenergy projects creates uncertainty for investors and developers, who may face bureaucratic hurdles in navigating regulatory requirements. Without streamlined policies and a clear regulatory framework, bioenergy projects may face prolonged timelines and increased costs, deterring private-sector participation and limiting sectoral growth (How et al., 2019; Albahnasawi et al., 2024).

Moreover, Malaysia lacks an integrated strategy to align bioenergy with broader energy policies. Effective tools such as carbon taxes and emissions trading, widely adopted in other countries, remain underutilized, leaving bioenergy projects struggling to compete with cheaper fossil fuels. Implementing targeted reforms, including streamlined approval processes, carbon pricing mechanisms, and subsidies for advanced bioenergy technologies, could reduce both financial and regulatory barriers. These changes are critical to fostering bioenergy growth and ensuring it contributes meaningfully to Malaysia's renewable energy goals and net-zero commitments.

4.5 Environmental and Logistical Concerns

The environmental implications of bioenergy production also raise concerns, particularly in terms of land use, water consumption, and potential pollution. Large-scale bioenergy projects may require substantial land, leading to land-use changes that can impact biodiversity and disrupt local ecosystems. Similarly, certain bioenergy processes, such as fermentation and anaerobic digestion, require significant water resources, which can strain local water supplies, particularly in regions where water availability is already limited (Albahnasawi et al., 2024). These environmental concerns necessitate careful planning and impact assessment to ensure that bioenergy development aligns with sustainability goals and does not inadvertently harm local environments.

Logistical challenges related to the collection, transportation, and processing of biomass feedstocks are also significant barriers to bioenergy production. Agricultural waste is often dispersed across rural areas, making it difficult to efficiently collect and transport to bioenergy facilities. The high moisture content of some agricultural residues, such as rice straw, requires drying before processing, adding to logistical costs, and complicating storage and transportation. Without efficient logistical systems, the cost-effectiveness and feasibility of bioenergy production are compromised, limiting the scalability of bioenergy projects in Malaysia.

5. POTENTIAL STRATEGIES FOR SUSTAINABLE AGRICULTURAL WASTE UTILISATION FOR BIOENERGY IN MALAYSIA

The sustainable conversion of agricultural waste into bioenergy presents a powerful strategy to meet Malaysia's energy needs while addressing environmental concerns. With an abundance of agricultural waste Malaysia has significant potential to capitalize on these biomass resources for renewable energy production. Achieving sustainable bioenergy generation from agricultural waste requires targeted strategies, ranging from advanced technological approaches to supportive policy frameworks. This section outlines several promising strategies, including wet torrefaction, thermochemical conversion, biochar production, biomass pelletization, co-production of biochar and electricity, and policy support, each offering unique benefits and challenges.

5.1 Wet Torrefaction and Anaerobic Digestion

Wet torrefaction is a promising pre-treatment method for enhancing anaerobic digestion, particularly for biohydrogen production from palm oil residues like empty fruit bunches (EFB). This process involves heating EFB in water under controlled temperatures and durations, breaking down the biomass structure and increasing its digestibility. Wet torrefaction produces a liquid substrate with enhanced properties for anaerobic digestion, resulting in a significant increase in biohydrogen yield (Aziz et al., 2024). Biohydrogen is a clean, high-energy biofuel, and its production from agricultural waste aligns well with Malaysia's renewable energy goals. Optimizing the conditions for wet torrefaction such as temperature, duration, and biomass-to-water ratio has been shown to improve biohydrogen yield, making it an efficient method for sustainable biomass conversion.

Anaerobic digestion, especially with pre-treated substrates, offers Malaysia a viable pathway to convert agricultural waste into biogas and biohydrogen, both of which are renewable fuels with various applications. In addition to producing energy, anaerobic digestion of EFB and other agricultural wastes provides environmental benefits by reducing the methane emissions associated with open decomposition. The process also generates a nutrient-rich digestate, which can be applied as a soil amendment, further contributing to a circular economy approach in agriculture.

5.2 Thermochemical Conversion Technologies

Thermochemical conversion technologies (including gasification, pyrolysis, and combustion) are effective in converting agricultural waste into bioenergy, providing a flexible approach that is adaptable to various biomass feedstocks. These technologies require minimal pre-treatment, making them cost-effective options for agricultural residues such as palm kernel shells, rice husks, and wood waste.

Gasification involves heating biomass at high temperatures with limited oxygen, converting it into synthesis gas (syngas) composed primarily of hydrogen, carbon monoxide, and methane. Syngas can be used for electricity generation, heating, or even further refined into biofuels. Gasification of palm kernel shells and wood waste is particularly promising in Malaysia, as it provides a high-energy alternative to fossil fuels, and requires minimal post-processing (Rahim et al., 2023; Teh et al., 2021).

Pyrolysis, another thermochemical process, heats biomass in the absence of oxygen, producing bio-oil, syngas, and biochar. While bio-oil can be refined into liquid fuels, biochar holds significant environmental value, as discussed in the next section. Pyrolysis is particularly suitable for agricultural residues with high lignocellulosic content, offering Malaysia an efficient way to produce both energy and carbon-sequestering biochar.

Combustion is the simplest thermochemical process, involving the direct burning of biomass to generate heat and power. Although it is less efficient than gasification and pyrolysis, combustion is widely used due to its low cost and simplicity. Combustion technologies can be adapted for various scales, from large power plants to small-scale rural applications, making them ideal for areas with limited access to advanced bioenergy infrastructure.

5.3 Biochar Production

Biochar production via slow pyrolysis is a highly sustainable approach for utilizing agricultural waste, with benefits extending beyond energy production. Biochar is a carbon-rich material that can be applied to soil, enhancing its water retention, nutrient content, and overall fertility. Additionally, biochar serves as a carbon-sequestration tool, locking carbon in a stable form that prevents its release into the atmosphere. Studies have shown that biochar production from Malaysian agricultural waste can achieve a net-negative global warming potential, positioning it as a promising negative emissions technology (Saharudin et al., 2024).

Beyond environmental benefits, biochar offers economic advantages as well. The increased crop yields from biochar-enriched soils reduce reliance on chemical fertilizers, which in turn lowers agricultural costs. This approach aligns with Malaysia’s carbon neutrality goals by reducing greenhouse gas emissions and enhancing sustainable agricultural practices. Integrating biochar production with other bioenergy processes such as co-production of biochar and electricity provides a multifunctional solution for agricultural waste management, carbon sequestration, and energy production.

5.4 Biomass Pellets

Biomass pellet production is a practical and environmentally friendly strategy to convert agricultural waste into a renewable fuel source. Pellets made from EFB, rice husks, and other residues offer several advantages, such as uniform size, high energy density, and ease of storage and transportation. Compared to raw biomass, pellets have lower moisture content and ignite faster, making them an

efficient and viable biofuel option for industrial boilers and small-scale heating applications (Mustafa et al., 2023).
The production of biomass pellets also enables the use of agricultural residues that would otherwise go to waste. Pellets can be easily transported to power plants or other bioenergy facilities, enabling centralized energy production from distributed agricultural waste sources. This method reduces the environmental impact of traditional waste disposal practices, such as open burning, and provides a renewable energy source that contributes to Malaysia's sustainable energy landscape.

5.5 Co-production of Biochar and Electricity
Co-producing biochar and electricity from agricultural residues, particularly oil palm waste, represents a powerful approach for carbon management and renewable energy generation. This process involves gasifying or pyrolyzing agricultural waste to produce biochar and syngas, which can be used to generate electricity. The dual benefits of biochar and electricity production make this approach economically attractive, as it not only produces energy but also sequesters carbon, supporting Malaysia's carbon neutrality targets (Su et al., 2023).

The co-production approach is especially valuable in rural areas, where biochar can be applied to local soils to enhance agricultural productivity. Electricity generated from syngas provides clean energy for local communities, promoting rural development and reducing dependence on fossil fuels. The economic benefits of this strategy include revenue from biochar sales, reduced costs associated with chemical fertilizers, and potential income from carbon credits. By enabling carbon sequestration and renewable energy generation, the co-production model aligns with Malaysia's environmental and economic sustainability goals.

5.6 Policy and Economic Considerations
Supportive policy frameworks and economic incentives are crucial for advancing sustainable agricultural waste utilization in Malaysia. The Malaysian government has implemented various policies to encourage renewable energy, but additional measures specific to bioenergy from agricultural waste are necessary. Policies such as feed-in tariffs (FiT) tailored for bioenergy, tax incentives for bioenergy investments, and subsidies for bioenergy infrastructure can lower the financial barriers to entry and encourage the adoption of waste-to-energy technologies (Kamaruzaman et al., 2023).

Regulatory reforms that streamline project approval processes and create clear guidelines for bioenergy development are essential for industry growth. Introducing carbon pricing or emissions trading schemes can also enhance the economic viability of bioenergy projects by allowing stakeholders to monetize the environmental benefits of carbon reduction. Additionally, government initiatives focused on recycling and waste-to-energy practices in the agricultural processing industry, particularly in the palm oil sector, can help transform waste into valuable energy resources (Yow et al., 2024; Rashidi et al., 2022).

Beyond domestic policies, Malaysia could benefit from international partnerships and technology transfer agreements to access advanced bioenergy technologies and best practices. Collaboration with neighboring ASEAN countries, for example, could facilitate the sharing of resources, technology, and expertise, boosting Malaysia's capacity for sustainable bioenergy production from agricultural waste.

5.7 Addressing Remaining Challenges
While these strategies present a comprehensive approach to sustainable agricultural waste utilization, several challenges remain. High initial costs, logistical barriers, and technological limitations hinder the large-scale implementation of bioenergy projects. Advanced technologies such as wet torrefaction and gasification require further development to enhance efficiency and scalability. Additionally, the economic feasibility of these technologies is often limited by market instability and competition with low-cost fossil fuels.

To overcome these challenges, a collaborative effort among government agencies, private sector stakeholders, research institutions, and local communities is essential., Technological advancements in biomass pre-treatment and conversion processes can improve the efficiency and cost-effectiveness of bioenergy production. Public-private partnerships can help secure funding and share the financial risks of bioenergy projects, while research institutions can contribute by developing innovative solutions tailored to Malaysia's unique biomass profile.

6. FUTURE DIRECTIONS AND RECOMMENDATIONS

Malaysia's agricultural sector generates substantial biomass waste each year, mainly from palm oil, rice, rubber, and coconut industries. While traditionally managed through environmentally detrimental practices like open burning and landfill disposal, this waste holds significant potential for renewable energy production. Transforming agricultural waste into bioenergy could play a crucial role in meeting Malaysia's sustainable energy goals, advancing rural economic development, and addressing the nation's commitments to reducing greenhouse gas (GHG) emissions and combating environmental degradation.

A systematic approach is critical for aligning bioenergy production with Malaysia's net-zero emission goals and renewable energy objectives. To achieve this, a phased strategy is recommended:

a. Short-term goals (2025-2030): Promote pilot projects for bioenergy technologies such as anaerobic digestion and pyrolysis, especially in areas with high agricultural waste production. These projects can help demonstrate feasibility, build local expertise, and create initial momentum for bioenergy adoption.

b. Mid-term goals (2031-2040): Scale up successful technologies to industrial levels by incentivizing private investment and implementing supportive policies, such as subsidies for bioenergy plants and tax incentives for innovative solutions. Expanding infrastructure and enhancing supply chains will be critical during this phase to support large-scale adoption.

c. Long-term goals (2041-2050): Achieve nationwide adoption of integrated bioenergy systems, leveraging advancements in carbon capture and storage (CCS) to ensure negative emissions. This stage focuses on optimizing efficiency and integrating bioenergy with broader renewable energy frameworks to secure its role as a cornerstone of Malaysia's energy landscape.

This roadmap should be complemented by regular monitoring and evaluation to track progress toward net-zero targets, ensuring the strategy remains flexible and responsive to technological, economic, and policy developments.

7. CONCLUSION

This review highlights the considerable bioenergy potential of Malaysia's agricultural waste and identifies the key challenges currently impeding its full utilization. Among the main barriers are technical limitations, high capital and operational costs, limited public awareness, regulatory gaps, and logistical difficulties in collecting and transporting biomass. Without targeted interventions, these barriers may continue to hinder the scalability and viability of bioenergy projects, slowing Malaysia's progress toward a low-carbon economy. To overcome these challenges and enhance Malaysia's bioenergy readiness, several strategies are recommended:

- Adopt Advanced Bioenergy Conversion Technologies: Technologies such as wet torrefaction, anaerobic digestion, biomass pelletization, and biochar production are particularly well-suited for maximizing the energy yield from Malaysia's agricultural residues. Implementing these technologies could increase conversion efficiency and mitigate environmental impacts, such as methane emissions from POME and air pollution from open burning.

- Implement Policy and Economic Incentives: Policy support is critical for the growth of Malaysia's bioenergy sector. Specific subsidies, tax credits, and feed-in tariffs for bioenergy projects can reduce financial barriers, making bioenergy more competitive with fossil fuels. Additionally, establishing carbon pricing and emissions trading schemes would allow bioenergy producers to monetize carbon reduction benefits, enhancing economic viability. A streamlined regulatory framework and clear guidelines for bioenergy development would further facilitate sector growth.
- Foster Community Engagement and Public Awareness: Social acceptance and community involvement are vital to the success of bioenergy initiatives. Educating rural communities about the environmental and economic benefits of bioenergy, particularly as an alternative to open burning, can foster social acceptance and encourage local participation in bioenergy projects. Public-private partnerships (PPPs) and international collaborations can provide the resources, technology transfer, and expertise needed to scale bioenergy, particularly in rural areas where agricultural waste is abundant.
- Encourage International Collaboration and Technology Transfer: Malaysia could benefit from partnerships with countries that have advanced bioenergy sectors. Collaboration with neighboring ASEAN countries could facilitate the exchange of resources, technology, and expertise, boosting Malaysia's capacity for sustainable bioenergy production from agricultural waste.

By implementing these strategies, Malaysia can effectively utilize its agricultural waste to meet a substantial portion of its renewable energy requirements. Converting biomass into bioenergy not only aligns with the nation's renewable energy objectives but also reduces dependency on imported fossil fuels, offering a sustainable alternative to conventional waste disposal practices. Bioenergy thus presents an integrated solution for Malaysia to achieve environmental sustainability, economic resilience, and rural development simultaneously.

In conclusion, Malaysia possesses both the resources and the potential to transform its agricultural waste into a valuable source of bioenergy. Although significant challenges remain, a coordinated approach encompassing technological advancements, supportive policies, community engagement, and international collaboration will enable Malaysia to overcome these obstacles and unlock the full potential of bioenergy. With strategic initiatives and sustained commitment, Malaysia can turn agricultural waste from an environmental liability into a cornerstone of its renewable energy landscape, contributing to a cleaner, greener future.

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