Progress in Energy and Environment

Journal homepage: https://www.akademiabaru.com/submit/index.php/progee
Link to this article: https://doi.org/10.37934/progee.27.1.1122

Volume 27 (2024) 11-22

Review Article

Current energy recycling technology for agricultural waste in Malaysia

Hui Ming Yow[1], Amir Abdul Razak[2,3,*], Adel Aboulqasim Alheemar[1,3]

[1] Energy Sustainability Focus Group (ESFG), Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang, Malaysia
[2] Centre for Sustainability of Ecosystem and Earth Resources (Earth Centre), Universiti Malaysia Pahang, Malaysia
[3] Researches Center and Manufacturing, Benghazi, Libya

[*] **Correspondence email:** amirrazak@umpsa.edu.my

Abstract

This article examines the production and use of biomass as a renewable energy source in Malaysia, focusing on the agricultural processing industry. Malaysia produces approximately 168 million tonnes of biomass, including palm oil waste, rice husks, coconut debris, sugar cane waste, urban waste, and forestry waste. The abundance of biomass resources provides a competitive advantage over other renewable energy sources. However, the industry faces restrictions and challenges, such as high disposal costs, high electricity consumption, and related expenses. To address these issues, it is crucial to study the types of biomass available, current technology for biomass energy production (waste-to-energy), and relevant environmental motivations, initiatives, and legislation. This paper analyses the agricultural waste available for energy generation, existing technologies for converting waste into energy, and the role of environmental policies in the agricultural processing business. Energy recycling, which involves utilizing agricultural waste to generate electricity and thermal energy, is proposed as a viable solution. Several technologies are explored, including anaerobic digestion, gasification, incineration/combustion, and pyrolysis, each with advantages and disadvantages. Thermochemical processes are highlighted for their effectiveness, requiring minimal pre-treatment, shorter reaction times, and adaptability to various biomass feedstocks and climatic conditions. The implementation of incentives, initiatives, and policies by the Malaysian government serves as guidelines for the agricultural processing industry to adopt energy recycling practices. By emphasising energy sustainability and promoting green building initiatives, the industry can contribute to a more sustainable and environmentally friendly energy landscape.

Article Info

Received 27 June 2023
Received in revised form 19 November 2023
Accepted 18 December 2023
Available online 15 January 2024

Keywords

Biomass
Energy sustainability
Sustainable
Agricultural
Green building

1 Introduction

Energy is essential to life, and fossil fuel depletion has become a global issue. Coal, oil and natural gas are widely used fossil fuels in developed and developing countries. The agricultural processing industry heavily depends on fossil fuels and contributes significantly to greenhouse gas emissions (GHG). The bulk of CO_2 emissions from fossil fuel burning are emitted by power production, industrialization, mobility, and commercial and residential construction, contributing to approximately 66% of global

CO_2 emissions [1]. In 2019, the gross final energy usage of all energy sources worldwide was 379 EJ; renewable energy accounted for 17% of the total [2].

Renewable energy is central to achieving international goals: increasing energy efficiency and access to renewable energy [3]. Renewable energy sources have emerged as a significant contributor to global energy production, accounting for approximately 50% of new energy capacity, according to the International Energy Agency (IEA). These sources have become the second most vital electricity supply after coal. Furthermore, the IEA projects a substantial increase in global electricity demand, estimating a 70% surge by 2040 [4].

Malaysia's extensive biomass reserve, estimated at over 168 million tonnes, includes palm oil waste, rice bran, coconut debris, sugar cane, urban waste, and forestry waste, offering significant potential for energy production, with a capacity of up to 2400 MW from biomass sources [5]. In alignment with the National Biomass Strategy 2020 framework, Malaysia aims to achieve an annual biomass production of 80 million tonnes by 2020. To ensure responsible waste management practices, the government has implemented stringent environmental targets, promoting the adoption of stricter waste management protocols within the processing industry [5].

The utilization of waste as a valuable resource for resource recovery is gaining significant momentum in waste management practices. Adopting energy generation techniques that utilize agricultural waste produced by the agricultural processing industry can result in energy savings and waste reduction, thus exemplifying the value of waste [6]. This paper provides an overview of agricultural waste and examines existing energy recycling technologies suitable for the respective waste types. The review encompasses a discussion on the available agricultural waste in Malaysia that can be effectively used for waste-to-energy purposes, recent technology advancements applicable to energy recycling, and the advantages, disadvantages, and existing supportive incentives, initiatives, and policies relevant to the agricultural processing industry.

2 Biomass waste for energy in the agricultural processing industry

Biomass, the fourth largest global energy source comprising 51 EJ of global energy supply, contributes around 16% of the total energy consumption, with palm oil accounting for 51% and agricultural waste accounting for 22%. There are massive benefits of using biomass resources as a fuel in generating renewable energy, including the fact that biomass resources are carbon neutral, reduce overreliance on fossil fuels, save money on fossil fuels, provide a source of revenue for manufacturers, and reduce garbage in landfills. Biomass is a carbon-neutral resource; the amount of carbon released into the atmosphere is equivalent to the amount absorbed by plants over their life cycle.

Researchers have shown significant interest in converting biomass into biochar as an economically viable and environmentally sustainable approach for waste recycling and environmental protection [7]. Biomass, the fourth largest global energy source, contributes 51 EJ to the global energy supply [8]. This resource accounts for approximately 16% of the total energy consumption, with palm oil constituting 51% and agricultural waste representing 22% of the biomass composition. Utilizing biomass resources as fuel for renewable energy generation offers substantial advantages, including carbon neutrality, reduced reliance on fossil fuels, cost savings, revenue generation for manufacturers, and waste reduction in landfills. It is worth noting that biomass is a carbon-neutral resource, as the carbon released during its use is offset by the carbon absorbed by plants throughout their life cycle [9,10].

Table 1 Malaysia biomass production [11–13].

Source	Source (kilo tonne)	Components for RE	Quantity (kilo tonne)	Moisture content (wt%)
Oil Palm	95700	Oil palm fronds	1150	60
		EPFB	76560	50-75
		POME	57420	80-95
Coconut	561	Coconut husk	190	11.5
Cocoa	0.76	Cocoa pod	0.56	12.58

The agro-based industries, such as agricultural processing, also contribute to biomass resources. Agricultural processing is a manufacturing subcategory that processes raw materials and intermediary goods produced from agriculture, comprising refining agricultural products [14].

Malaysia is the second largest producer and exporter of palm oil, having cultivated over 5 million hectares of arable land production, contributing to 31% of global output. The large size of land yields 80 million tons of fresh fruit bunches (FFB) annually. FFB is commonly processed into crude palm oil (CPO) and palm kernel oil (PKO) for utilization in industries such as food, fuels, and chemical industries [15]. Almost 70% of the fresh fruit bunch volume is wasted [16]. As technology advances and the agricultural processing industry expands in response to the growing demand for food and improvements in human quality of life, more emphasis has been placed on utilizing additional biomass resources. These resources include rice husk, sugarcane, cocoa, and coconut. Biomass resources, as depicted in Fig. 1, have proven to be valuable sources of energy generation through efficient recycling processes. According to the data presented in Table 1, oil palm stands out as the biomass source with the highest number of components for renewable energy production. Various parts of the oil palm plant can be effectively utilized in energy recycling. Oil palm shells are particularly prevalent in the current market as a widely used resource for generating renewable energy. Oil palm is the preferred choice for renewable energy generation due to its low moisture content level, approximately 7%, the lowest among the various biomass components considered. Rice husk, with a moisture content of 9%, closely follows oil palm shells and exhibits significant potential for application in renewable energy production. In contrast, biomass resources such as sugarcane bagasse and coconut husk possess higher moisture contents of 50% and 11.5%, respectively, indicating that rice husk is more suitable for energy generation.

However, biomass resources with high moisture content, such as oil palm trunks with a moisture content of 75%, require additional drying processes before they can be effectively utilized as a fuel in the green industry for renewable energy generation [12]. These drying procedures ensure that the moisture content of the biomass is reduced to an optimal level, enhancing its suitability for efficient energy conversion. By addressing the moisture content, biomass resources like oil palm trunks can be effectively harnessed as a valuable fuel source in the green industry, supporting renewable energy generation.

Oil palm	Coconut	Cocoa	Rice	Sugar cane
• Empty fruit bunch • Shell • Trunks • Fiber	• Husk • Coconut shell	• Pod husk • Bean shell	• Rice husk • Straw	• Bagasse

Fig. 1 Biomass resources in Malaysia.

3 Energy recycling

Electricity energy in Malaysia is generated both by fossil fuel and renewable resources. Fossil fuel energy consumption comprises biodiesel, coal, petroleum, and natural gas products. International Energy Agency, Energy Balance for Non-OECD Countries – 2012 Edition reported that the rate of energy imports had grown rapidly at 7.2% per year to accommodate rising energy demands of 5.8% per year [18]. Malaysia will have to import fossil fuels to offset its dependency due to its heavy demand for fossil fuels and the decrease of local fossil fuel reserves. It is critical to have a well-balanced fuel mix of fossil and renewable sources. Besides, it was published in Malaysia Energy Statistics Handbook 2020 that the total energy consumption increased rapidly year by year from 13,122 ktoe in 1990 to 64,658 ktoe in 2018 [19].

Energy recycling (waste-to-energy) restores energy that would otherwise be lost in industrial processes by flaring, releasing it to the surroundings, or using less efficient machinery. It can be converted instead into usable energy, such as electricity or heat (steam or heated water) [20].

Malaysia possesses abundant biomass resources and encompasses a land area totaling 32.90 million hectares, presenting a significant opportunity for the agricultural processing industry to contribute to energy recycling. The distribution of crops in Malaysia is as follows: oil palm accounts for 35.2%, rubber for 2.3%, and other crops such as cocoa, coconut, paddy, and others collectively contribute 29.3% [21,22]. In recent scientific discourse, considerable attention has been directed toward plant biomass as an alternative to fossil fuels. The renewable nature of biomass has emerged as a significant factor in this interest [23]. Notably, biomass possesses distinct advantages over other renewable energy sources as it has the potential to cater to the entire spectrum of energy requirements, encompassing heating/cooling, electricity, and fuels, without encountering significant storage challenges. Additionally, biomass exhibits versatility in its conversion into solid, liquid, and gaseous energy sources through various thermo-chemical, physical-chemical, and biochemical processes. These processes enable the generation of power, fuels, and heating/cooling through combustion or complete oxidation.

4 Types of technology for energy recycling

Agro-based industries produce agricultural waste as a result of agricultural activities. One of the agricultural wastes in Malaysia is biomass which produces at least 168 million tonnes annually [24]. Malaysia critically requires effective waste treatment facilities and infrastructure to address its waste issues, as recycling alone might not be sufficient. Previously, waste incineration was the preferred method for reducing waste volume and destroying dangerous substances, minimizing human health risks [25]. These include material recovery facilities or recycling plants, composting plants, anaerobic digesters, and waste-to-energy plants in the current era [26]. When considering electricity yields and heat, incineration seems to be the best option; however, if solely considering electricity production, anaerobic digestion might be better [27]. As a result, appropriate utilization of waste's energy potential through economically and technically viable solutions can aid in promoting sustainability and fulfilling global renewable energy demand [28]. Table 2 summarises the possible energy recycling technology in its respective industry and fields.

Table 2 Types of technology and the related industry/field.

Technology	Industry / Field
Anaerobic digestion plant	Palm oil biomass, food processing industry
Gasification	Household waste, coconut, palm kernel shell
Direct combustion	Municipal solid waste (MSW), palm oil biomass
Combined heat process plant (CHP)	Municipal solid waste (MSW), palm oil biomass
Pyrolysis	Palm oil biomass

Fig. 2 shows the conversion process flow of the biomass-to-energy technology for energy recycling to heat and electricity generation, including the fuel produced from each technology.

Biomass may be converted into liquid or gaseous fuels and then used to produce power, heat, chemicals, or liquid or gaseous fuels. Biomass can be turned into biofuels in many ways, roughly categorized into thermochemical conversion and biochemical conversion. Thermochemical conversion is an effective method for turning biomass into biofuels that may be categorized into two groups: dry (nonaqueous) and hydrothermal methods. Temperature, heating rate, residence time, particle size, and other physical properties are utilized to determine whether thermochemical conversion methods are appropriate [29]. The fundamental for biochemical conversion is the enzymatic hydrolysis of lignocellulosic materials to sugars, which are subsequently fermented and distilled to make cellulosic ethanol [30]. Table 3 provides a broad comparison of thermochemical and biological processes.

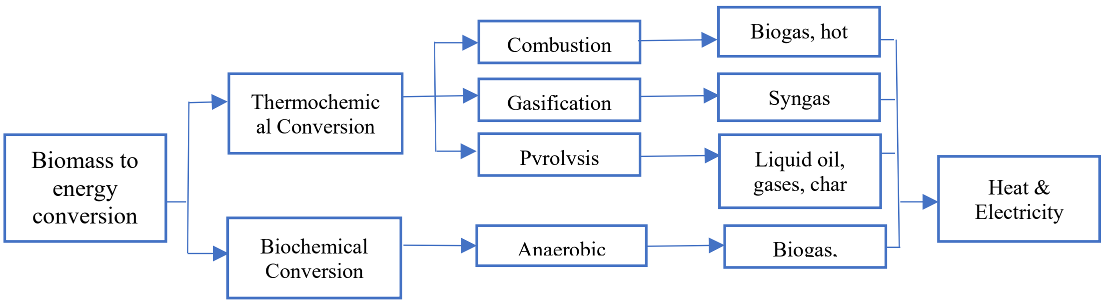

Fig. 2 Biomass-to-energy conversion for energy recycling.

Table 3 Comparison between Thermochemical and Biochemical Processes [30].

Thermochemical Process	Biochemical Process
Effectively utilized **with** most biomass feedstock	Microbes, enzymes, and chemicals are used
There is no **pre-treatment**	Pre-treatment is necessary
It has **higher** productivity due to the reaction's wholly chemical nature.	Productivity is limited due to biological conversion.
Using fractional separation of products, many high-value products are possible.	It is restricted to one or a few products, requiring more microbes and enzymes for additional products.
Regardless of weather conditions	Sensitive to ambient temperature, anaerobic digester
Waste/biomass is fully utilized.	Secondary wastes, such as biomass sludge, are produced.
Reaction time is shortened.	Reaction time is lengthened.

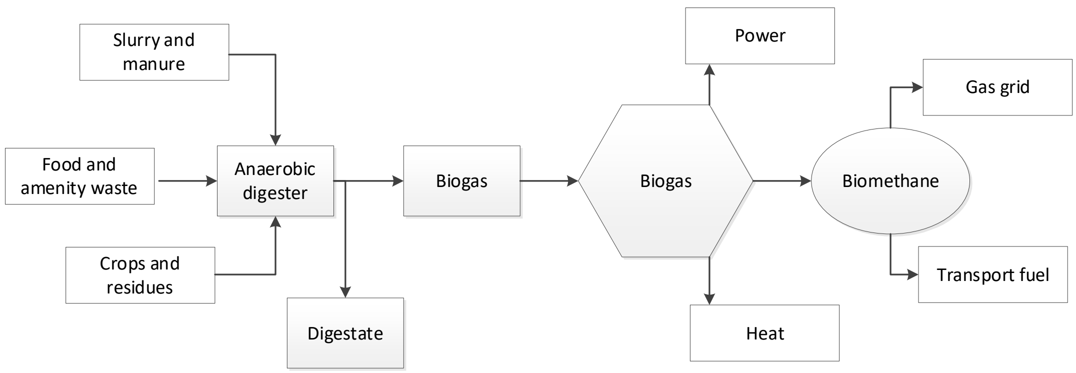

Fig. 3 Anaerobic Digestion Plant [31].

Anaerobic digestion plant (ADP) is today a proven and environmentally acceptable waste treatment process widely utilized in Europe, and anaerobic digestion is classified as one of the biological treatments available in the market [32]. The overview of the plant processes is shown in Fig. 3. Suitable feedstocks for ADP are agricultural waste, livestock waste, forestry residues, energy crops, and urban solid waste [33]. Thus, ADP breaks down the waste produced in the food manufacturing industry by microorganisms without air. It is a naturally occurring technique that produces biogas, which is composed of 60% methane (CH4) and 39% carbon dioxide (CO2), along with traces of water vapor, hydrogen, sulfide, and ammonia [34]. Methane gas (biogas) can generate sustainable heat and power or be processed into 99% methane and converted into bio-methane for industrial usage [31]. This procedure also created a residual co-product consisting of an odorless "digestate" containing high volumes of plant-available nitrogen, phosphorous, and potassium and may be distributed on the ground as fertilizers [35]. Balance in the ecosystem can be achieved as the agricultural waste from the food manufacturing industry can be returned to the environment and help grow new plants.

In Malaysia, the anaerobic digestion plant generates biogas using food waste as the potential feedstock. However, compared to other organic wastes, such as food waste, palm oil mill effluent (POME) is given more significant consideration as a source [36]. POME is an underutilized liquid waste stream yielded during the palm oil extraction/decanting phase that is a desirable raw material for biomethane generation and is widely present throughout all palm oil mills that can consistently provide substrates for biogas production at no or low cost and is an excellent source of potential for biomethane production. Two methods are applied in palm oil mills: the open pond and closed anaerobic systems. The open pond system, which is relatively inexpensive to install, is the most widely used. However, this system usually fails to fulfill discharge standards due to failed operational control, longer retention time, and worries about short-circuiting. In addition, biogas produced in an open system is not collected for use. Due to the recoverable methane, a confined anaerobic system, instead of an open system, may create and capture top-quality methane-rich biogas from POME [37].

4.1 Gasification

Biomass gasification reduces reliance on fossil fuels by substituting biomass resources for fossil fuels, assuming that adequate biomass feedstock is available abundantly. Biomass gasification is a biomass energy-based system that produces energy through the combustion of biomass resources in the gasifier at a high temperature of about 1000°C [38]. The first reported use of gasification for electrical generating occurred in 1792. However, Siemens erected the first operational gasifier device in 1861, establishing the first industrial coal gasification station at Wabash River, United States of America, 1999. Since 2001, biomass gasification has attracted substantial interest due to variable oil costs and global warming concerns [39].

The products of biomass gasification are combustible gaseous gas called syngas/producer gas production, hydrogen-enriched gas production, electricity production, and biomass gasification co-generation. Syngas/producer gas is a combustible gaseous gas produced from the inadequate combustion of solid biomass fuel to create syngas. As a result, flammable gases such as carbon monoxide (CO), hydrogen (H2), and traces of methane (CH4), as well as byproducts like tar and dust, are created. Syngas/producer gas may be used to power internal combustion engines and can also be utilized to manufacture methanol, which can be used as a fuel for heat engines and as a chemical feedstock for industrial. The thermochemical route of biomass gasification produces hydrogen at a lower cost with higher efficiency than biochemical routes, which face a significant challenge – a low rate of hydrogen production. However, they are less energy-intensive and better for the environment [40]. Co-generation is a technique for enhancing biomass gasification's economic and environmental elements, whereas electricity resulting from co-generation is a widespread potential use of biomass gasification [41].

Biomass gasification's benefits include sustainability and being environmentally friendly - better efficiency, lower CO2 emissions, and improved soil fertility as the biochar produced can act as a medium for carbon storage and sequestration [42]. In Malaysia, waste-to-energy (WTE) plays a critical role in household solid waste management, eliminating roughly 95% of municipal solid waste (MSW) by volume entering landfills through thermo-chemical waste treatment pathways such as gasification [43]. With the fluidization method, the study demonstrated that considerable quantities of hydrogen gas (up to 67 mol%) may be produced from agricultural waste such as coconut and palm kernel shells [44].

4.2 Direct Combustion

The primary method employed for waste management involves the combustion and conversion of waste materials at a minimum temperature of 850 °C, generating heat and energy [32]. However, large-scale industries often utilize non-conventional power plants that exhibit inefficiencies in electricity production. This inefficiency arises from the significant energy loss (60-70%) during the process, as well as the time required for the cooling tower to lower the temperature of the boiled water and initiate the cycle again. Compared to landfill gas recovery systems (LFGRS) and anaerobic digestion, a case study conducted at the Taman Beringin dump in Malaysia demonstrated that incineration has the highest potential for energy output, heat generation, and electricity production. Notably, incineration yielded the most significant profit increase, reaching 287% (450 TUSD/d), followed by anaerobic digestion and

LFGRS. Based on the analysis, incineration is the most cost-effective and environmentally sustainable option among the available alternatives [45].

Conventional power plants (CHP) typically generate 30-40% of electricity [46]. In contrast, CHP systems capture and utilize the heat that would otherwise be wasted during electricity generation, distributing it to nearby buildings for various heating purposes. CHP, also known as co-generation, enables simultaneous electricity and heat production, providing users with power and hot water. CHP systems can achieve an impressive efficiency of approximately 90% for electricity and heat generation [46]. The size of a CHP system may vary depending on individual user requirements. In Brazil, a study evaluated the feasibility of utilizing agricultural and agro-industrial wastes as renewable resources for combustion in centralized power plants to generate electricity. The research findings revealed a significant potential for renewable energy production, estimated at 141 TWh per year [47].

In Malaysia, the waste-to-energy sector primarily relies on two prominent technologies: incineration in combined heat and power plants (CHP) and controlled landfill systems designed to capture methane emissions. These technologies have gained prominence due to several factors, including the substantial volume of municipal solid waste (MSW) generated daily in urban areas and the significant presence of palm oil biomass waste, a primary agricultural resource [48].

Incineration in CHP plants is a widely adopted waste-to-energy technology in Malaysia. It involves the controlled burning of waste materials, such as MSW, to generate heat and electricity simultaneously. This approach offers a dual benefit by addressing waste management concerns while harnessing the energy potential of the waste stream. Through the combustion process, the waste materials are thermally treated at high temperatures, converting them into heat energy to generate electricity. The generated electricity can then be supplied to the grid for consumption, contributing to the overall energy supply. Controlled landfill systems, on the other hand, focus on capturing and utilizing methane gas, a potent greenhouse gas released during the decomposition of organic waste in landfills. With specialized techniques and infrastructure, methane emissions are collected, controlled, and converted into usable energy sources. This process reduces the release of methane into the atmosphere, mitigates its environmental impact, and allows for the extraction of valuable energy from the waste stream. This recovered energy can be utilized for various purposes, including electricity generation and heat production. Adopting CHP systems in waste-to-energy facilities offers additional advantages beyond energy production. The production of biogas as a byproduct of the waste treatment process enables efficient energy recovery and promotes energy savings. Biogas, primarily composed of methane and carbon dioxide, can be harnessed as a renewable energy source. It can be used as a substitute for fossil fuels, reducing dependency on non-renewable resources and minimizing greenhouse gas emissions.

4.3 Pyrolysis

Pyrolysis is a highly efficient thermochemical conversion process that enables the conversion of lignocellulosic biomass into valuable gaseous and liquid fuels through the decomposition of biomass into charcoal and volatile matter. To ensure effective conversion, municipal solid waste (MSW) needs to be reduced to a maximum size of 300 mm, requiring pretreatment methods [49]. Pyrolysis encompasses slow and rapid conversion processes characterized by specific parameters such as temperature, heating rate, and process duration. In the absence of oxygen, pyrolysis occurs at temperatures around 500°C, initiating a gradual chemical reaction that transforms the biomass into three primary products: oil, gas, and char. These products find applications in various industrial processes and refining operations [50]. The gas produced during pyrolysis is a mixture of hydrocarbon-rich gases, including CO_2, CH_4, and H_2. This gas mixture can be utilized in industrial applications, such as heat and power generation, or further processed to produce valuable chemicals and fuels [50]. Additionally, pyrolysis generates a fluid oil product that can be readily employed in different applications without further upgrading. This oil can be used in boilers, furnaces, turbines, and diesel engines, providing a versatile and readily available fuel source [51].

The oil palm industry generates significant byproducts, accounting for approximately 90% of the total palm oil production. These byproducts include empty fruit bunches, oil palm shells, oil palm fiber, and palm oil mill effluent (POME), while only 10% constitutes the actual palm oil produced in the oil palm mill. Among the various thermal energy conversion technologies, pyrolysis has emerged as a promising and efficient method for utilizing these oil palm byproducts to generate renewable energy [52]. However, the government has identified landfill gas recovery systems (LFGRS), combustion, anaerobic digestion, and gasification as the preferred technologies for waste-to-energy conversion. Although a promising technique, pyrolysis is not currently listed among the four waste treatment options considered the most effective for waste-to-energy conversion in the country [27].

5 Incentive, initiative, and policies for energy recycling in Malaysia

5.1 Incentive

The government of Malaysia is diligently trying to strengthen renewable energy (RE) policies, programs, and incentives to encourage and expand the use of RE resources. In addition, the Malaysian government has provided many incentives, such as pioneer status (PS) and investment tax allowance (ITA), to encourage the country's growth of renewable energy [53].

The Sustainable Energy Development Authority (SEDA) has implemented several programs to promote the usage of renewable energy (RE), including the Green Investment Tax Allowance (Project) and the Green Income Tax Exemption (GITE) (Services). Renewable Energy, Energy Efficiency, Green Building, Green Data Centers, and Integrated Waste Management Activity are included in the GITA of 100% of qualified capital expenditure (QCE) until 2023 [54]. For GITE, 100% of tax payable from the year of evaluation when MIDA received the application until 2023, which covers Renewable Energy, Energy Efficiency, Green Building, Green Data Centre, Green Township, Certification/Verification Bodies, and Electric Vehicles (EV) [54].

5.2 Initiative

Sustainable development initiatives are currently being pursued extensively worldwide [53]. Several projects are underway to encourage the long-term exploitation of Malaysia's biomass resources. The 11th Malaysia Plan (2016-2020) states that research would be carried out to identify new RE sources to broaden the power mix. Through the Sustainable Energy Development Authority (SEDA), the government will train 1,740 people to become professionals in the field of RE [55]. Additionally, the 11th MP emphasizes the handling of solid waste as a new resource that may be recovered materially via biochemical (AD) or thermo-chemical (Incineration, Pyrolysis, Plasma Gasification) routes for electrical production and secondary fuel resources for energy production [43]. Renewable energy sources of biomass, biogas, solar PV, and mini-hydro are expected to make up 7.8% of Peninsular Malaysia and Sabah's total installed capacity by 2020, or about 2,080 MW6 [55]. Moreover, the 11th MP wants to make Malaysia a much more energy- and resource-efficient country by, among other things, managing waste more holistically, increasing the amount of renewable energy in the energy market and the national mix of electricity generation, and setting up a green market.

5.3 Policy

Malaysia has dedicated over three decades to formulating and refining pivotal policies and strategies to effectively address the complex aspects of energy production, delivery, and demand. These critical initiatives are primarily devised and implemented by government-linked entities and other governmental organizations [56].

The Feed-in Tariff (FiT) system has emerged as a highly effective approach for facilitating the rapid and sustained deployment of renewable energy (RE). Under this mechanism, Distribution Licensees (DLs) are obligated to purchase electricity generated from renewable sources from Feed-in Approval Holders (FIAHs) for a specified duration [54]. This incentivizes electricity consumers exceeding a monthly consumption threshold of 300kWh to generate renewable electricity and sell the surplus back to the grid [55]. FiTs have been widely adopted in over 40 countries worldwide, including prominent examples such as Germany, Spain, Italy, and Thailand. These tariff schemes compensate producers for the electricity they supply from renewable sources, calculated in kilowatt hours (kWh) [50]. Notably, FiTs encompass various renewable energy technologies such as solar PV, biomass, biogas, and mini-hydro, with their inclusion dating back to 2011.

Despite its prior existence in Malaysia, a tariff system for renewable energy has not gained significant popularity. However, in 2011, a revised version of the Feed-in Tariff (FiTs) was introduced to enhance the effectiveness of the previous tariff structure (refer to Table 4). The primary objective of the new FiTs is to encourage a more significant number of Malaysians to participate in renewable energy investments. The highest biomass tariff is RM 0.31kWh^{-1} and the lowest is RM 0.27kWh^{-1}, with a 0.5% degression [57].

Table 4 Rates of FiTs for biomass [58].

Biomass (Solid Waste)	FiTs Rates(RM/kWh)
(a) FiT tariffs for installed capacity at a basic level:	
(i) Up to and including 10 MW	0.3085
(ii) 10–20 MW	0.2886
(iii) 20–30 MW	0.2687
(b) Bonus FiT rates that meet one or more of the following criteria:	
(i) Utilisation of gasification technology	+0.0199
(ii) Utilisation of steam-based electricity generation systems with **greater** than 20% overall efficiency	+0.0100
(iii) Utilisation of a boiler or gasifier that was made or constructed locally	+0.0500
(iv) Utilisation of solid waste as a source of energy	+0.0000

6 Conclusion

This paper provides a comprehensive review of the available biomass waste in Malaysia, including oil palm, coconut, cocoa, rice, and sugarcane, highlighting their potential for energy utilization in the agricultural processing industry. Malaysia's abundance of biomass resources signifies a significant opportunity for energy recycling and sustainable waste management practices. Among the various biomass waste sources, oil palm stands out as the country's primary contributor to biomass waste production. The paper also examined different technologies for energy recycling, encompassing thermochemical conversion methods such as combustion, gasification, and pyrolysis, as well as biochemical conversion methods like anaerobic digestion. The advantages and disadvantages of these technologies were thoroughly assessed.

The Malaysian government has also implemented attractive incentives, initiatives, and policies to promote adopting sustainable energy practices, fostering awareness and participation in developing a greener future. Energy recycling benefits the environment and offers industry advantages, including waste reduction, energy savings, and cost efficiency. Based on the extensive literature review, it was observed that anaerobic digestion plants had gained prominence as the preferred technology for energy recycling and the generation of renewable energy through waste-to-energy conversion in the agricultural processing industry. However, it is worth noting that pyrolysis, although a promising technology, remains relatively less explored and adopted compared to other reviewed technologies. Further research and development efforts should be directed towards investigating and promoting the potential of pyrolysis in the Malaysian context, given its ability to convert biomass waste into valuable energy resources effectively.

In conclusion, the findings of this paper underscore the importance of energy recycling and the utilization of biomass waste in Malaysia's agricultural processing industry. The identified technologies and government initiatives provide a framework for sustainable waste management practices and for developing a greener energy sector. Continued exploration of innovative and efficient energy recycling technologies, including further investigation into pyrolysis, will contribute to Malaysia's transition towards a more sustainable and environmentally friendly future.

Acknowledgement

The authors wish to thank Universiti Malaysia Pahang for the facilities and financial support under grant RDU210306.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party to the publication of the current work.

ORCID

Amir Abdul Razak https://orcid.org/0000-0001-5479-7025

References

[1] S. Mah Abdullah, Carbon dioxide emissions causing global warming, New Straits Time, 2017. Retrieved from: https://www.nst.com.my/opinion/columnists/2017/12/313842/carbon-dioxide-emissions-causing-global-warming (accessed Jan. 09, 2024).

[2] A. Sertolli, Z. Gabnai, P. Lengyel, and A. Bai, Biomass Potential and Utilization in Worldwide Research Trends—A Bibliometric Analysis, Sustainability 14(9) (2022) 5515. https://doi.org/10.3390/su14095515.

[3] REN21, Why is renewable energy important, 2019. Retrieved from: https://www.ren21.net/why-is-renewable-energy-important/.

[4] Acciona, Renewable Energy. Retrieved from: https://www.acciona.com/es/energias-renovables/.

[5] The Star, Green Energy Source Going to Waste, 2018. Retrieved from: https://www.mida.gov.my/home/7148/news/green-energy-source-going-to-waste/.

[6] M. Maisarah, C. P. Chien Bong, W. S. Ho, J. S. Lim, Z. A. Muis, H. Hashim, S. Elagroudy, G. L. Hoh Teck, and C. S. Ho, Review on the suitability of waste for appropriate waste-to-energy technology, Chemical Engineering Transaction 63 (2018) 187–192. https://doi.org/10.3303/CET1863032.

[7] C. C. Chang and R. Li, Agricultural waste, Water Environment Research 88(10) (2016) 1334–1373. https://doi.org/10.1002/wer.1211.

[8] J.-F. Mercure and P. Salas, An assessement of global energy resource economic potentials, Energy 46(1) (2012) 322–336. https://doi.org/10.1016/j.energy.2012.08.018.

[9] SynTech Bioenergy, Biomass Advantages and Disadvantages, 2017. Retrieved on: https://www.syntechbioenergy.com/blog/biomass-advantages-disadvantages (accessed Jan. 09, 2024).

[10] L. Chen, G. Msigwa, M. Yang, A.I. Osman, S. Fawzy, D.W. Rooney, and P.-S. Yap, Strategies to achieve a carbon neutral society: a review, Environmental Chemistry Letters 20(4) (2022) 2277–2310. https://doi.org/10.1007/s10311-022-01435-8 (accessed Jan. 09, 2024).

[11] Malaysian Palm Oil Board (MPOB), Palm Oil Extraction Rate, Malaysian Palm Oil Board (MPOB), 2023. Retrieved from: https://bepi.mpob.gov.my/index.php/oil-extraction-rate (accessed Jun. 07, 2023).

[12] E. K. New, T. Y. Wu, S. K. Tnah, A. Procentese, and C. K. Cheng, Pre-treatment and sugar recovery of oil palm fronds using choline chloride:calcium chloride hexahydrate integrated with metal chloride, Energy 277 (2023) 127486. https://doi.org/10.1016/j.energy.2023.127486.

[13] M. H. Zakaria, R. Abu Dardak, and M. F. Ahmad, Business Potential of Coconut-based Products in the Global Markets | FFTC Agricultural Policy Platform (FFTC-AP), FFTC Agricultural Policy Platform (FFTC-AP), 2022. Retrieved from: https://ap.fftc.org.tw/article/3046 (accessed Jun. 07, 2023).

[14] W. C. Government, Agri-Processing, 2019. Retrieved from: https://www.elsenburg.com/content/agri-processing (accessed Jan. 09, 2024).

[15] B. B. Nyakuma, Biomass Energy Outlook in Malaysia using Functions of Innovation Systems, Preprints (Basel) (2018) 2018020158 https://doi.org/10.20944/preprints201802.0158.v1 (accessed Jan. 09, 2024).

[16] S. Zafar, Biomass Energy Prospect in Malaysia, 2017. Retrieved from: https://www.cleantechloops.com/biomass-energy-in-malaysia/ (accessed Jan. 09, 2024).

[17] S. Mekhilef, R. Saidur, A. Safari, and W. E. S. B. Mustaffa, Biomass energy in Malaysia: Current state and prospects, Renewable and Sustainable Energy Reviews 15(7) (2011) 3360–3370. https://doi.org/10.1016/j.rser.2011.04.016.

[18] Suruhanjaya Tenaga Energy Commission, Energy in Malaysia: Towards a Brighter Future; Suruhanjaya Tenaga Energy Commission: Putrajaya, Malaysia, 2017.

[19] Suruhanjaya Tenaga Energy Commission, Malaysia Energy Statistics Handbook, Department of Energy Management and Industrial Development Suruhanjaya Tenaga (Energy Commission), 2020. Retrieved

from https://www.st.gov.my/en/contents/files/download/116/Malaysia_Energy_Statistics_Handbook_20201.pdf (accessed Jan. 09, 2024).
[20] PrimaryEnergy.Com, Energy Recycling: Turning Waste Heat into Added Power, 2018. Retrieved from: https://www.primaryenergy.com/energy-recycling/ (accessed Jan. 09, 2024).
[21] Ministry of Economy Malaysia, Statistic of Major Agriculture Product, Agriculture Division, Ministry of Economy Malaysia, 2023. Retrieved from: https://www.epu.gov.my/en/socio-economic-statistics/economic-statistics/statistic-major-agriculture-product (accessed Jun. 21, 2023).
[22] Department of Statistics Malaysia, Selected Agricultural Indicators, Malaysia 2022, 2022. Retrieved from: https://www.dosm.gov.my/portal-main/release-content/selected-agricultural-indicators-malaysia-2022 (accessed Jun. 21, 2023).
[23] M. Ioelovich, Recent findings and the energetic potential of plant biomass as a renewable source of biofuels - A review, Bioresources 10(1) (2015) 1879–1914. https://doi.org/10.15376/biores.10.1.1879-1914.
[24] S. Yasmeen and N. Yuvarani, Creating Wealth from Waste: Towards Sustainable Agriculture, 2019. Retrieved from: https://ikp.upm.edu.my/artikel/creating_wealth_from_waste_towards_sustainable_agriculture-51163 (accessed Jan. 9, 2024).
[25] B. Z. Bajić, S. N. Dodić, D. G. Vučurović, J. M. Dodić, and J. A. Grahovac, Waste-to-energy status in Serbia, Renewable and Sustainable Energy Reviews 50 (2015) 1437–1444. https://doi.org/10.1016/j.rser.2015.05.079.
[26] S. Leoi Leoi, Malaysia is overflowing with waste and we're running out of options, 2019. Retrieved from: https://www.thestar.com.my/lifestyle/living/2019/07/16/plastic-waste-landfills (accessed Jan. 9, 2024).
[27] S. T. Tan, W. S. Ho, H. Hashim, C. T. Lee, M. R. Taib, and C. S. Ho, Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia, Energy Conversion and Management 102 (2015) 111–120. https://doi.org/10.1016/j.enconman.2015.02.010.
[28] A. H. Bhatt and L. Tao, Economic perspectives of biogas production via anaerobic digestion, Bioengineering 7(3) (2020) 1–19. https://doi.org/10.3390/bioengineering7030074.
[29] J. Zhang and X. Zhang, The thermochemical conversion of biomass into biofuels, in: Biomass, Biopolymer-Based Materials, and Bioenergy, 2019, pp. 327–368. https://doi.org/10.1016/B978-0-08-102426-3.00015-1.
[30] R. Singh, A. Prakash, B. Balagurumurthy, and T. Bhaskar, Hydrothermal Liquefaction of Biomass, in: Recent Advances in Thermochemical Conversion of Biomass, 2015, pp. 269–291. https://doi.org/10.1016/B978-0-444-63289-0.00010-7.
[31] N. T. B. Consultants, About Anaerobic Digestion, 2019. Retrieved from: http://www.biogas-info.co.uk/about/ (accessed Jan. 9, 2024).
[32] M. Maisarah, C. P. Chien Bong, W. S. Ho, J. S. Lim, Z. A. Muis, H. Hashim, S. Elagroudy, G. L. Hoh Teck, and C. S. Ho, Review on the suitability of waste for appropriate waste-to-energy technology, Chemical Engineering Transaction 63 (2018) 187–192. https://doi.org/10.3303/CET1863032.
[33] K. Moustakas, P. Parmaxidou, and S. Vakalis, Anaerobic digestion for energy production from agricultural biomass waste in Greece, Energy 191 (2020) 116556. https://doi.org/10.1016/j.energy.2019.116556.
[34] H. W. Yen and D. E. Brune, Anaerobic co-digestion of algal sludge and waste paper to produce methane, Bioresource Technology 98(1) (2007) 130–134. https://doi.org/10.1016/j.biortech.2005.11.010.
[35] Powersystems, Anaerobic Digestion (AD) A Renewable Energy Technology, 2019. Retrieved from: https://www.powersystemsuk.co.uk/anaerobic-digestion/anaerobic-digestion-renewable-energy-technology/ (accessed Jan. 9, 2024).
[36] P. Y. Hoo, H. Hashim, W. S. Ho, and S. T. Tan, Potential Biogas Generation from Food Waste through Anaerobic Digestion in Peninsular Malaysia, Chemical Engineering Transaction 56 (2017) 373–378. https://doi.org/10.3303/CET1756063.
[37] J. Langerak, POME as a Source of Biomethane, BioEnergy Consult, 2020. Retrieved from: https://www.bioenergyconsult.com/tag/what-is-pome/ (accessed Jan. 9, 2024).
[38] M. Abed, A. M. Radwan, and A. Amin, Review of Biomass Thermal Gasification, 2017. Retrieved from https://www.intechopen.com/books/biomass-volume-estimation-and-valorization-for-energy/review-of-biomass-thermal-gasification (accessed Jan. 9, 2024).
[39] P. Basu, Biomass Gasification and Pyrolysis: Practical Design and Theory. 2010.

[40] P.T.Sekoai and M.O.Daramola, Biohydrogen production as a potential energy fuel in South Africa, Biofuel Research Journal 2(2) (2015) 223–226.
[41] S. Farzad, M. A. Mandegari, and J. F. Görgens, A critical review on biomass gasification, co-gasification, and their environmental assessments, Biofuel Research Journal 12 (2016) 483–495. https://doi.org/10.18331/BRJ2016.3.4.3.
[42] S. L. Narnaware and N. L. Panwar, Biomass gasification for climate change mitigation and policy framework in India: A review, Bioresource Technology Report 17 (2021) 100892. https://doi.org/10.1016/j.biteb.2021.100892.
[43] Z. J. Yong, M. J. K. Bashir, C. A. Ng, S. Sethupathi, J. W. Lim, and P. L. Show, Sustainable Waste-to-Energy Development in Malaysia: Appraisal of Environmental, Financial, and Public Issues Related with Energy Recovery from Municipal Solid Waste, Processes 7(10) (2019) 676. https://doi.org/10.3390/pr7100676.
[44] W. A. W. Ab, K. Ghani, R. A. Moghadam, M. A. M. Salleh, and A. B. Alias, Air Gasification of Agricultural Waste in a Fluidised Bed Gasifier: Hydrogen Production Performance, Energies 2(2) (2009) 258–268. https://doi.org/10.3390/en20200258.
[45] S. Tan, H. Hashim, C. Lee, M. R. Taib, and J. Yan, Economical and environmental impact of waste-to-energy (WTE) alternatives for waste incineration, landfill and anaerobic digestion, Energy Procedia 61, (2014) 704–708. https://doi.org/10.1016/j.egypro.2014.11.947.
[46] Chris, Combined heat and power (CHP) co-generation, Retrieved from: https://www.explainthatstuff.com/combinedheatpower_cogeneration.html (accessed Jan. 9, 2024).
[47] J. Portugal-Pereira, R. Soria, R. Rathmann, R. Schaeffer, and A. Szklo, Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil, Biomass Bioenergy 81 (2015) 521–533. https://doi.org/10.1016/j.biombioe.2015.08.010.
[48] O. Sadeghi, A. Fazeli, and M. Bakhtiarinejad, An Overview of Waste-to-Energy in Malaysia, 2015 Applied Mechanics and Materials 695 (2014) 792–796. https://doi.org/10.4028/www.scientific.net/AMM.695.792.
[49] L. Lombardi, E. Carnevale, and A. Corti, A review of technologies and performances of thermal treatment systems for energy recovery from waste, Waste Management 37 (2015) 26–44, https://doi.org/10.1016/j.wasman.2014.11.010.
[50] E. Onoja, S. Chandren, F. I. Abdul Razak, N. A. Mahat, and R. A. Wahab, Oil Palm Biomass in Malaysia: The Present and Future Prospects, Waste Biomass Valorization 10(8) (2019) 2099–2117. https://doi.org/10.1007/s12649-018-0258-1.
[51] S. D. Anuar Sharuddin, F. Abnisa, W. M. A. Wan Daud, and M. K. Aroua, A review on pyrolysis of plastic wastes, Energy Conversion Management 115 (2016) 308–326. https://doi.org/10.1016/j.enconman.2016.02.037.
[52] N. Abdullah, F. Sulaiman, and Z. Aliasak, A Case Study of Pyrolysis of Oil Palm Wastes in Malaysia, AIP Conference Proceeding 336 (2013) 331–336. https://doi.org/10.1063/1.4803619.
[53] H. Hashim and W. S. Ho, Renewable energy policies and initiatives for a sustainable energy future in Malaysia, Renewable and Sustainable Energy Reviews 15(9) (2011) 4780–4787. https://doi.org/10.1016/j.rser.2011.07.073.
[54] SEDA Malaysia, Renewable Energy Incentives. Retrieved from: http://www.seda.gov.my/reportal/re-incentive (accessed Jan. 9, 2024).
[55] Economic Planning Unit, MALAYSIA: The Eleventh Malaysia Plan 2016-2020, 2016. Retrieved from: https://www.ekonomi.gov.my/sites/default/files/2021-05/Chapter%201.pdf (accessed Jan. 9, 2024).
[56] M. Ozturk, N.Saba, V. Altay, R. Iqbal, K.R. Hakeem, M. Jawaid, F.H. Ibrahim, Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia, Renewable and Sustainable Energy Reviews 79 (2017) 1285–1302, https://doi.org/10.1016/j.rser.2017.05.111.
[57] Renewable Energy World, Malaysia's 2011 Proposed Solar, Biomass, Biogas, & Hydro Tariffs, 2010. Retrieved from: https://www.renewableenergyworld.com/2010/08/16/malaysias-2011-proposed-solar-biomass-biogas-hydro-tariffs/ (accessed Jan. 9, 2024).
[58] Sustainable Energy Development Authority Malaysia (SEDA), FiT Dashboard, Sustainable Energy Development Authority Malaysia (SEDA). Retrieved from: https://www3.seda.gov.my/ (accessed Jan. 9, 2024).