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Review Article

Methane Biogas Production in Malaysia: Challenge and Future Plan

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Biomethane is a sustainable energy that is produced from an organic and renewable resource. As the second-largest oil palm producer in the world, palm oil mill effluent (POME) is the primary source of biomethane generation in Malaysia. POME is the by-product of palm oil extraction and is extensively employed as a feedstock for the production of biomethane. Malaysia has an equatorial environment with humid and hot weather; this climate is conducive to the cultivation of numerous agricultural crops. A considerable number of agricultural wastes and residues are produced by agricultural crops, however, only 27% of them are used as fuel or to create useable products. Several publications have been published on the production of biomethane from POME; nevertheless, additional research is required on the use of other bioresources and technologies for biomethane production in Malaysia. In addition, there is a lack of comprehensive information on the future development of biomethane production in Malaysia; thus, to fill this gap, this review paper focuses on the challenges and future of Malaysia, which puts an emphasis on POME and also includes other alternative options of bioresources that can be the future feedstock for biomethane production in Malaysia. To the best of our knowledge, this is the first paper to provide a comprehensive overview of the biogas trend in Malaysia in terms of challenges and current biomethane development, as well as detailed information on a number of leading companies that are currently active in Malaysia biogas industry.

1. Introduction

Biomethane is a purified biogas and a renewable alternative to natural gas that is often created by anaerobic digestion of organic materials such as agricultural waste, dead animal, and plant matter, manure, sewage, and organic waste [1]. The production of biomethane in Malaysia reached a peak in 2016 due to the abundance of feedstock such as POME, which is primarily derived from palm oil production. This is further confirmed by the fact that Malaysia is one of the world's leading suppliers of palm oil [2]. There are numerous ongoing improvements in biomethane production, particularly regarding the utilization of suitable feedstock, which have attracted the government's attention through national economic essential schemes such as the Feed-in Tariff (FIT) initiative [3]. In terms of the overall market trend of biomethane production in Malaysia, there is a gradual increment of activity in the biogas industry starting from 2016 until 2018. In 2018, a total of 30 biogas plants with a combined capacity of 55.83 MW were installed as part of FIT projects, whereas in 2017, only 18 biogas plants with a capacity of 30.89 MW were installed. This demonstrates an increase in capacity installed over time [4]. In addition, Malaysia's National Renewable Energy Policy and Action Plan seek to install 4,000 MW of renewable energy capacity by 2030, of which 410 MW is designated for biogas capacity [5].

Furthermore, biomethane is a helpful energy source that is not only renewable but also environmentally benign. Although biomethane contains some greenhouse gases, it does not contribute to global warming. Burning biomethane will not increase atmospheric carbon dioxide levels since biomethane is an organic substance and the carbon dioxide produced will decay spontaneously [6]. Four phases are involved in the anaerobic digestion of biomethane: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is a process that simplifies complicated chemical compounds. The process of acidogenesis converts simpler chemicals into volatile fatty acids from simpler molecules [7]. The subsequent phase is acetogenesis, in which volatile fatty acids, methanol, and ethanol are consumed by acetogenic bacteria and transformed into acetic acid, hydrogen, and carbon dioxide. In the last stage, when methanogens convert readily available compounds such as volatile fatty acids, methanol, and ethanol into methane and carbon dioxide, biogas is produced [6, 8].

Numerous review articles have been published on biomethane production, with the majority focused on POME-based biomethane if they pertain to the Malaysia case study. Zainal et al. reviewed relevant literature on the integrated system technology of POME treatment for not only biomethane but also biohydrogen, revealing the present technology and its benefits [7]. Sarwani et al. assessed the potential for biomethane generation from POME and its usage in a petrol car in Malaysia, while Hoo et al. discovered the ideal planning for biomethane injection into the natural gas grid in Malaysia [9, 10]. Further research is required to identify any potentially viable bioresources in Malaysia for biomethane production. In addition, there is a paucity of knowledge on the future development of biomethane production in Malaysia; therefore, to fill this void, this review paper focuses on the challenges and future of Malaysia, with an emphasis on POME and other alternative bioresource options that can be the future potential feedstock for biomethane production in Malaysia. To gain a deeper understanding of the current status of biomethane development in Malaysia, Table 1 provides a summary of a recent study on the biogas industry in Malaysia from 2018 to 2022, which also highlights the motivation of conducting this study.

2. Potential of Malaysia's Biomass for Biomethane Production

2.1. Palm Oil-Based Biomass. Malaysia is the second-largest producer of palm oil worldwide. In 2019, 19.6 million tonnes of crude palm oil were produced from 98.28 million tonnes of fresh fruit brunches FFB processed by 452 palm oils mills, from 5.9 million hectors of oil palm planted areas [2]. During the production of crude palm oil, a large amount of water is required, 5 to 7.5 m^3 of water will be used to produce one ton of crude palm oil. A large amount of wastewater also known as palm oil mill effluent (POME) is generated, about 50% of the production of crude palm oil. The palm oil industry can generate approximately 50 to 65 million tonnes of POME in Malaysia annually [21].

The POME contains high organic content, causing the water to consist of a high level of chemical oxygen demand (COD) and biochemical oxygen demand (BOD). When POME is discharged into water, it turns the water into brown color, and the water becomes smelly and slimy [22]. This may cause oxygenation and may kill fishes or other aquatic organisms furthermore denying humans to get clean and high-quality water for domestic use. Besides, the untreated POME on soil alters its physic-chemical properties by decreasing pH and increasing salinity, making the soil undesirable for planting [23]. Unfortunately, most POME is discharged directly into nearby streams or rivers and on land. Therefore, the direct discharge of POME will lead to an environmental pollution problem. Figure 1 shows the POME and Table 2 shows the characteristic POME.

On the other hand, POME can be treated and converted to biogas to avoid pollution of the environment whereby every 1 m^3 of treated POME is expected to yield up to 34 Nm^3 biogas comprising 54.4% or 12.36 kilograms of methane. Biogas has a calorific value of 17.9–29.9 MJ/Nm^3 due to the high concentration of methane, making it a viable alternative to natural gas for power production [8]. Biological treatment is used to treat around 85% of POME in Malaysia. POME's biological treatment consists of several pond systems, including anaerobic, facultative, and aerobic pond systems. The treated POME's final effluent must meet the discharge criteria specified by the Malaysian Department of Environment (DOE) before being discharged. It is necessary to have an efficient management system in place for the treatment of waste or by-products to safeguard the environment and prevent the deterioration of air and river water quality [25].

2.2. Agriculturally Based Biomass. Malaysia is located in the equatorial region, it is hot and humid throughout the year and this climate is ideal for plant growth. Thus, Malaysia is one of the countries with active agricultural activities, Malaysia has a lot of biomass resources that can be used to convert into alternative energy or useful eco-products. A minimum of 168 million tonnes of biomass waste is generated in Malaysia annually [26]. The major agricultural crops planted in Malaysia are rubber (39.67%), oil palm (34.56%), cocoa (6.75%), rice (12.68%), and coconut (6.34%) [27]. There is a large number of residues generated but only a small amount of them are used and they are mostly disposed of or burned. Instead of being discharged like trash, they should be turned into valuable products. Agricultural waste has the potential for generating biomethane due to its low moisture and high fiber content. They are rich in lignin, cellulose, hemicellulose, and other carbohydrates which are appropriate to be used in the process of anaerobic digestion

Table 1: State-of-the-art overview of the study conducted for Malaysia biomethane production (2018–2022) that includes the justification of conducting this study.

Year	Author	Title	Outcome/Significant of the study	Remarks
2018	[11]	Progress of biogas industry in Malaysia: cattle manure (CM) as potential substrate for biogas production and issue and challenges	(i) According to the analysis, CM can produce 1,650,463 kW·hr of electrical energy, which is equivalent to 1.2% of the biogas plant's current power production in Malaysia (ii) In 2020, based on an annual growth rate of 0.6% for the cow population, it is anticipated that 0.56 million cattle will generate 28,150 m^3 of methane (CH_4) per day and have the capacity to generate 1,670,268 kWh per day.	(i) This paper's main focus revolves on the usage of cattle manure as potential feedstock for biogas production
2018	[12]	Economic feasibility of feed-in tariff (FiT) for biomethane injection into natural gas distribution grid	(i) According to preliminary findings, the FiT rate ranges from 40.81 to 227.85 MYR/GJ for biomethane production units located within 1,000 m of the injection point and of four different sizes: 250 m^3/h, 500 m^3/h, 750 m^3/h, and 1,000 m^3/h. (ii) On the basis of the rising trend of piped gas prices and the government's subsidy rationalization strategy, it is anticipated that biomethane, given the right policy regulations and FiT mechanism, can be a renewable gas as competitive as natural gas.	(i) This paper's main focus is to evaluate on the FiT mechanism implementation in Malaysia with economic assessment consideration
2019	[9]	Biomethane from palm oil mill effluent (POME): transportation fuel potential in Malaysia	(i) It was discovered that a palm oil mill in Malaysia is capable of producing 1,000 to 4,200 tonnes of biomethane per year and can power 1,309, 2,129, and 3,240 cars annually, depending on its size. (ii) The finding indicates that approximately 103,091 cars in Malaysia can be fueled with biomethane annually.	(i) The companies involved for biogas capture was briefly mentioned without any detail explanation (ii) The entire paper focused was mainly on utilizing biomethane as transportation fuel only
2019	[13]	The potential of using biogas feeding for fuel cells in Malaysia	(i) By 2030, it is anticipated that palm oil residue will have the capacity to generate around 1,474 MW, a nearly 50 percent increase (ii) There is still a need for the government to build up a number of incentives, including subsidies as well as assistance and financing of biogas facilities and technology, despite its enormous potential in the energy production industry.	(i) This paper aims to identify the potential use of biogas to be fed to fuel cells, and determine the conservation of conventional resources and reduction of carbon dioxide (CO_2) emissions in electricity generation
2019	[7]	Integrated system technology of POME treatment for biohydrogen and biomethane production in Malaysia	(i) Compared to a single-stage system, an integrated system would have a better biogas generation rate and a higher percentage of COD removal efficiency. (ii) The two-stage fermentation method is more stable in terms of its operations and has a greater energy recovery rate.	(i) This paper reviewed relevant literature studies on treating POME and other organic waste using integrated bioreactor for biomethane production

Table 1: Continued.

Year	Author	Title	Outcome/Significant of the study	Remarks
2019	[14]	A review on life cycle assessment of biogas production: challenges and future perspectives in Malaysia	(i) Previous research from other countries indicates that the examination of biogas systems from a life cycle perspective could help optimize the biogas system. (ii) As for the scope of this study, it was divided into six categories: environmental performance, energy performance, energy and environmental performance, environmental and economic performance, energy, environmental and economic performance, and specific factors that influence biogas production performance.	(i) This paper highlights and discusses the feasibility of LCA approach on biogas production from POME as well as the opportunities and challenges from the Malaysian perspective.
2020	[15]	Economic feasibility of smart city power generation from biogas produced by food waste in Malaysia via techno-economic analysis	(i) According to the economic analysis, a 72 kW biogas plant could be constructed to provide around 630,000 kWh of power for 500 households at a unit production cost of 0.07 USD/kWh. (ii) Unfortunately, it takes approximately 11 years for a small biogas plant to recoup its initial cost.	(i) This paper give insight on economic feasibility of biogas production from municipal food waste for electricity generation to be utilized in existing and new township
2020	[16]	Biogas production optimization from palm oil mill effluent: experiments with anaerobic reactor	(i) This study shows that the biogas generation performance of CSTR might be enhanced by employing a POME substrate with the optimal C/N ratio and organic loading rate (OLR). (ii) The outcomes of this study would be useful for optimizing biogas production from POME as waste to energy (WtE) in palm oil mills.	(i) This paper aims to present research conducted on biogas production performance of anaerobic digestion process of palm oil mill effluent (POME)
2021	[17]	Strategies to promote biogas generation and utilisation from palm oil mill effluent (Malaysia)	(i) According to the findings, the construction of an integrated biogas and wastewater treatment system in a typical 60 t/h mill in Malaysia could export up to an average of 1.9 MW of electrical power. (ii) The effective deployment of an integrated biogas and wastewater treatment system reduces greenhouse gas emissions by 50,430 t CO_2 per year compared to the typical open ponding system used in the industry.	(i) The aim of this paper is to synthesize and optimize an integrated biogas and wastewater treatment system via a process systems engineering tool that yields maximum economic performance
2021	[1]	Review of biowastes to energy in Malaysia: Current technology, scalability and socioeconomic analysis	(i) Several concerns and challenges have been found for the transition from laboratory size to industrial scale, where parameters such as pH, temperature, organic loading rate (OLR), hydraulic retention time (HRT), and mixing rate must be properly managed (ii) The socioeconomic survey conducted as part of this study demonstrated the high acceptability of this technology and the population's eagerness to contribute and participate in this effort.	(i) This review paper focused on the current biogas technologies, their scalability and socioeconomic analysis on biowastes to energy in Malaysia.

Table 1: Continued.

Year	Author	Title	Outcome/Significant of the study	Remarks
2022	[18]	Evaluation of potential feedstock for biogas production via anaerobic digestion in Malaysia: Kinetic studies and economics analysis	(i) POME and food waste (FW) have the largest methane yields with biogas yields of up to 0.50 L/g VS, while landfill leachate has the lowest at 0.12 L/g VS. (ii) The economic study demonstrates that POME has the shortest payback period (PBP), the best internal rate of return (IRR), and the greatest net present value (NPV).	(i) This paper aims to determine the potential feedstocks for biogas production via AD based on their characteristics, methane yield, kinetic studies and economic analysis
2022	[19]	Waste-to-renewable energy Transition: Biogas generation for sustainable development (Malaysia)	(i) Animal manure in Malaysia can produce up to 1,317.20 mm^3/year of biogas, which can ultimately result in the production of 2.1 104 kWh/year of electricity (ii) Relevant policies for Malaysia to implement long-term biogas generation are discussed.	(i) The article consists of an explanation of various technologies of power generation utilizing municipal waste
2022	[20]	Recent challenges of biogas production and its conversion to electrical energy	(i) The findings of this review demonstrate that biogas is a good renewable energy since it addresses several problems and provides numerous benefits to humans. (ii) This comprises the substrates used, the operating settings, and the pretreatment employed in order to maximize the biogas yield.	(i) The review covers the recent challenges of biogas production and its conversion to electrical energy
2022	Our study	Methane biogas production in Malaysia: challenge and future plan	(i) Other potential feedstocks such as agriculturally based biomass, animal manure-based biomass and even algal-based biomass were thoroughly discussed (ii) System incorporated for biomethane production by companies like CENERGI, FGV, FutureNrg were also discussed (iii) Recent studies related to biomethane production such as biogas capture and the potential application and utilization of captured biogas was found emphasized on combined heat and power (CHP) for the production of steam and electricity	(i) This paper aims to provide an overview of Malaysia's biomethane production that is not limited to a single aspect, as it covers multiple aspects including challenges, current development, other potential feedstock for biomethane production, government incentives, and detailed information on a number of leading companies currently active in Malaysia's biogas industry.

[28]. Table 3 shows the advantage and limitations of producing biomethane from different types of agricultural waste.

2.3. Animal Manure-based Biomass. The demand for dairy products, beef, mutton, and poultry meat in Malaysia is rising in recent years. This causes an increase in the population of the livestock and hence increases the production of farm animal manures, resulting in the difficulty with the disposal of a large number of animal manures [31]. Animal manure is the mixture of animal feces, urine, bedding material, or other materials associated with animal production, they can be in the form of solid, semisolid, or liquid. Animal manure has a polluting impact on the environment if they are not managed or handled suitably. This is due to animal manure containing high concentrations of nitrogen and phosphorus which can cause nutrient imbalance and pollution in the environment [32]. Moreover, the farm animal manures may contain the residues of some harmful substances such as growth hormones, antibiotics, and heavy metals. Microorganisms in animal manures may also pollute the environment, which in turn causes the outbreak of human diseases. Hence, to prevent the animal manure from contaminating the environment, the animal manure is treated through an anaerobic digestion process which is degradation of organic compounds into simple substances by microorganisms under the condition of the absence of oxygen. The treated animal manure brings many beneficial outcomes like decreasing its polluting effect on the

Figure 1: Palm oil mill effluent (POME) [24].

Table 2: Characteristics of palm oil mill effluent (POME) [8].

Parameter	Concentration range
Chemical oxygen demand (COD) (mg/L)	15000–100000
Biochemical oxygen demand (BOD) (mg/L)	10250–43750
Total solid (mg/L)	11500–79000
Total suspended solids (mg/L)	5000–54000
Oil and grease (mg/L)	130–18000
Temperature (°C)	80–90
pH	3.4–5.2

environment, producing quality and organic fertilizer, reduction of odors and microbial pathogens with the sustainable production of energy source as biogas [32]. In terms of the type of animal manure in Malaysia, which is comprised of 306 million chickens, 0.7 million cattle, and 1.6 million pigs, it was estimated up to 1043 MW of energy recovery from these animal manures [4].

2.4. Algal-Based Biomass. Geographically and climatically, Malaysia has an abundance of potential for algae cultivation, which can be employed for biogas and even biodiesel production [33]. Third-generation feedstock algae serve as a crucial premise that prevents the need to compete with food supplies derived from first-generation feedstock, which could threaten national energy security. In addition, the use of algae eliminates the need for substantial investment due to the high cost of pretreatment for delignification and chemical processing of second-generation feedstock [34]. Although the cultivation of algae is still under development and requires additional study, numerous researchers have demonstrated the efficacy of algae for biogas production. For instance, the utilization of brown algae (seaweed), which is a type of macroalgae, through biochemical conversion technology is known as a potential source of anaerobic digestion (AD), which typically uses a direct way to obtain energy. One tonne of brown algae can produce around 20 m^3 of methane, which, when combined with natural gas, can power a 9.8 kW power plant [35]. It has been suggested that the usage of biogas obtained from seaweed could cut greenhouse gas emissions by 42% to 82% compared to natural gas [36]. In addition, Baltrenas and Misevicius conducted experimental studies that demonstrated the feasibility of macroalgae for biogas production. During the processing of the macroalgae spirogyra neglect, 1.32 m^3/m^3d of biogas was produced, while other biodegradable waste only produced 0.9 m^3/m^3d [37]. In Malaysia, efforts on algae use are mostly focused on biodiesel production, which necessitates a large-scale growth strategy for algae to meet the need for both biodiesel and biogas [38].

2.5. Municipal Solid Waste (MSW) Biomass. Malaysia is a developing country in Southeast Asia's core region, with a total size of 329,847 km^2. Throughout the year, Malaysia's population grows at a rate of 2.4% annually, or around 600.000 people every year [39]. This annual population growth results in a significant increase in municipal solid waste (MSW), particularly in urban regions. Apart from that, MSW is abundantly generated from papers, plastics, and food, accounting for up to 80% of total weight, owing mostly to Malaysia's growing industrialization and urbanization [40]. Malaysian MSW has increased by 91% during the last decade, ranging between 0.5 and 2.5 kg per capita per day [39]. In fact, in 2020, 29,472 metric tons of wastes are generated by Malaysians and these wastes are mostly emphasized on food waste and it is expected that by 2030, MSW that is generated in Malaysia will be 49,670 tonnes [41]. Therefore, food wastes can be used as a potential feedstock for the production of biogas as a strategy to address this issue. In a recent study, Lim et al. found that food waste has the largest methane yields with biogas yields of up to 0.50 L/g VS [18]. In addition, Hanif et al. demonstrated the viability of using household food waste, showing that a 72 kW biogas plant could be constructed to produce roughly 630,00 kWh of electricity for 500 households [15]. Further demonstrating the viability of using food waste as feedstock for biogas production in Malaysia, which is crucial for creating a circular economy, a biomethane potential test on food waste using a continuous anaerobic digestion system yields a maximum methane composition of 81% at 1.92 g COD/L [42].

2.6. Garden Waste (GW). Garden waste (GW) is a sort of waste that is typically generated during the construction of public parks and housing developments. This GW consists primarily of grass cuttings, which make up the majority of the biowaste collected from the nearby cities and villages [1]. In addition, in the same context as other wastes, GW is also abundantly generated and regularly disposed of in landfills and incinerators over the years, which also indicates the long-term trend of this waste's volume increasing over time. This has various repercussions, including land restriction, air pollution, and water contamination [1, 18] Therefore, instead of having a negative influence on the environment, GW can be further valorized and converted into valuable materials. Currently, waste management in Malaysia for GW focuses on composting and turning it into fertilizer, while GW utilization as feedstock for biomethane production has yet to grow significantly [18]. Several investigations have illuminated the potential of GW incorporation in biomethane production. Abreu et al., for instance, demonstrate the co-digestion of GW and food waste (FW) by means of a two-step hyper thermophilic-mesophilic process, with the

Table 3: Advantages and limitations of producing biomethane from different types of agricultural waste.

Type of agricultural waste	Advantages	Limitation	Reference
Cocoa	The cocoa pods and cocoa leaves contain carbon, nitrogen, protein, fat, and crude fiber which is needed by anaerobic digestion.	The carbon to nitrogen ratio may affect the production of the biomethane due to the carbon to nitrogen ratio which will inhibit the microbial activity in the degradation process.	[29]
Rice	The rice husk has low water content which can be used to produce a high level of biomethane by using solid state anaerobic digestion (SSAD).	Rice husk consists of a high amount of lignocellulosic content which is difficult to be degraded by microbes. Thus, rice husk must be treated before it is used to produce biomethane.	[27]
Coconut	The price of coconut waste is cheaper and can be obtained easily throughout the year.	The production of biomethane from the untreated coconut waste is low due to the coir pith of having a huge quantity of lignin, electrical conductivity, and total dissolved solid which is difficult for microbes to undergo degradation.	[30]

result indicating that a biomethane yield of 68214 $L \cdot kg^{-1}$ was achieved from the end products of GW: FW 90:10% co-fermentation [43]. Additionally, the energy produced by co-fermentation and anaerobic digestion of GW: FW 90:10% is 0.5 $MJ \cdot kg^{-1}$ and 24.4 $MJ \cdot kg^{-1}$, respectively [43]. Besides, this is consistent with Liczbiński and Borowski research which employs the similar co-digestion strategy with GW and kitchen waste and generates up to 387 NmL/gVS of biomethane output [44]. Therefore, these supporting arguments demonstrate that Malaysia can gradually implement GW for biomethane production, rather than focusing primarily on using GW for composting purposes.

2.7. Sewage Sludge (SS). Sewage sludge (SS) is a form of mud-like residue that is often created in huge quantities following the waste water treatment process. In Malaysia, it is anticipated that 3 million metric tonnes of SS are produced annually, and that this number would rise to 7 million metric tonnes by 2022 [18]. Agricultural use (42.4%), incineration (26.9%), landfilling (13.6%), and other methods such as composting and land reclamation are the usual methods of SS disposal [45]. However, untreated SS containing numerous harmful components and pathogens had a negative impact on both the environment and public health. As a result, as a means of mitigating this issue, anaerobic digestion is extensively used, whereby SS is further handled through this ecologically benign process that is biologically destroyed and turned into a form of biogas that is typically made of 48–65% methane [18, 45]. In addition, the created biogas could be employed for the generation of electricity [1]. Furthermore, a recent study by Al-samet et al. showed that mixing sewage sludge with food waste had a synergistic effect that increased the amount of methane produced and enhanced the efficiency of the anaerobic digestion process [46]. Moreover, Selamwit and Agizew conducted the biomethane potential analysis (BMP) on a lab scale, and the results showed that the energy recovered from SS has an electric potential of 8.81 kWh [47]. Additionally, under the premise of sustainability, SS can be seen as a renewable energy source, and its combustion produces significantly fewer greenhouse gas emissions than fossil fuel energy output. SS generates 58% fewer emissions than natural gas and 80% less than hard coal and fuel oil for the same amount of energy [48].

3. Challenges in Biogas Production in Malaysia

The palm oil sector has been the driving force of renewable energy in Malaysia, as well as one of the country's largest expenditures, accounting for up to 46% of global palm oil exports. This demonstrates how this industry's demand contributes to Malaysia's market economy. Palm oil mill effluent (POME) is one of the by-products generated by the palm oil industry. Most of the researchers, including Hoo et al., and Chelliapan et al., concur that the effluent is harmless [5, 25]. However, the POME by-product that is commonly employed as a feedstock for biomethane production in Malaysia has several severe downsides, and one of the primary concerns of the POME produced is its negative impact on the environment. Typically, considerable volumes of POME are created as a result of the oil extraction process. During the extraction of oil, the main component is only formed in small quantities. For instance, for every 1000 kg of processed fresh fruit bunches (FFB), 700 kg is generated as POME while the remaining is the palm oil [49]. This demonstrates how POME might be the primary source of environmental contamination in Malaysia if it continues untreated and unmanaged, which could result in pollution that is even more severe than that caused by municipal sewage. In addition, POME contains residual oil that may be detrimental to aquatic organisms and degrades the land through soil infusion and causing an imbalance of nutrient content, which may impede the growth of trees [25].

POME is a viscous, brownish liquid with a high concentration of both biological oxygen demand (BOD) and chemical oxygen demand (COD). In addition, the organic content, such as nitrogen and phosphorus, has a high value. If untreated, POME is dumped unrestrictedly into watercourses, these high-concentration constituents will have a significant deleterious impact on aquatic life [25]. A high concentration of these components will deplete the ocean's oxygen supply, causing aquatic organisms to suffocate and ultimately die. In the context of utilizing POME as a renewable energy source, the primary concern is that the biogas created during the decomposition of POME via anaerobic digestion is not fully recovered; instead, POME is allowed to dissipate into the atmosphere. According to Group and Gases, this not only wastes the full utilization of biogas but also causes greenhouse gas emission that leads to air pollution [8]. The gas emission contains components such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other gases whereby the accumulated gases in the atmosphere will further develop into global warming which adds to another environmental crisis caused by POME [50].

Another problem associated with biomethane production is during anaerobic digestion. At the end of the anaerobic digestion, there is a high potential for hydrogen sulphide (H_2S) to be produced which is very toxic and poisonous. Therefore, proper biogas cleaning is needed for the removal of this toxic compound [12]. An additional cost is also required to add H_2S removal units in biogas plants to overcome this problem. In Malaysia, fossil fuels are substantially subsidized, resulting in an unattractive market for innovative energy sources such as biogas. This could only be lowered with good implementation of technology and at the same time, the dependence on government subsidies can also be lowered. Moreover, the return on investment (ROI) for biogas production is low, which is primarily attributable to the absence of a holistic approach to controlling POME as well as the substantial capital expenditure required for the installation of digester tanks or covered lagoons [51]. In addition, there are multiple covered lagoons in each biogas plant, which implies that each lagoon has the POME of varying qualities. Therefore, without a proper system that can maintain the same quality of POME, the produced biomethane may contain undesirable components. Aside from this, the rapid expansion of the palm sector, which relies heavily on land utilization, generates debate regarding biodiversity loss and climate change. The development of projects, such as biomethane generation, has posed a major threat to biodiversity, particularly for endangered species, such as orangutans, Sumatran tigers, and elephants [52].

Moreover, the lack of incentive for the development of biomethane injection infrastructure is also one of the challenges faced in biomethane production in Malaysia that is due to high capital cost. This becomes unattractive for stakeholders not only to invest but also because of the lack of support for policy instruments [5, 49]. Other difficulties related to biogas generation in Malaysia involve the national grid connection. To prevent power loss, the distance between the biogas power plant and the distribution system's interconnection point must be less than 10 kilometers. However, this is not the case in Malaysia because rural areas, particularly in Sabah and Sarawak, are located far from the interconnection point. This causes complications, as longer connection distances necessitate greater connection investment. Apart from that, other technical challenges are from the specific characteristic of biogas itself that is highly influenced by the calorific value of biogas. The calorific value of biogas is based on the composition of biogas produced, which is often influenced by parameters such as feedstock composition, retention time, temperature, and input rate to the digester. Since the technology for biomethane generation in Malaysia is still in the process of development, controlling all of these parameters is a difficult aspect of biogas plants [51]. Due to limited space in biogas plants, other obstacles include energy storage for storing significant amounts of biomethane produced. This results in unutilized energy being wasted and discharged as greenhouse gas emissions. In an environmental context, biogas generation in Malaysia that utilizes the typical anaerobic digestion (AD) process necessitates an abundance of water, which could be an issue for rural areas in Malaysia, particularly during extremely dry seasons [53].

As indicated in the preceding section, the biogas industry in Malaysia is still in its infancy, and as a result, the majority of biomethane production technology, such as AD, is imported from Germany. In the long-term context, this is undesirable because it fosters reliance on imports and causes expensive equipment installation costs for the biogas plant. In addition, a lack of project coordination and implementation in biomethane plants are obstacles in the Malaysian biogas industry. In Malaysia, for instance, the majority of waste treatment relies solely on anaerobic digesters to break down waste with the aid of microorganisms, without including any biogas capture technology that can be attained through effective partnership with government organizations [54]. Moreover, the generation of biomethane in Malaysia is plagued by an interconnection issue involving such factors as load demand, distribution infrastructure, and cabling cost. From an economic standpoint, investors will only be interested in grid-connected biogas projects if the proposed mills are located in a region that has secured a reasonable FiT. In addition, Malaysia's lack of technical competence in biomethane plants hinders its ability to advance rapidly. The biogas plant's anaerobic digester requires an operator with the skills and knowledge to manage and monitor related technologies. Therefore, biomethane companies in Malaysia may have a difficult time implementing advanced technology in the future if there is a shortage of qualified personnel. Not only that, the information on biogas production in Malaysia is also limited due to the lack of systematic analysis with outdated documentations which become one of the constrains in the research development [55].

4. Biomethane Production Process and Plant in Malaysia

4.1. Anaerobic Digestion (AD). The conventional process of producing biomethane in Malaysia and even in many other developing countries like Germany, Poland, and Japan is through anaerobic digestion. The primary focus of anaerobic digestion (AD) in the past decades is mainly on treating municipal sludge generated by municipal wastewater treatment plants that help in reducing pollution [53]. The present approach to integrating with AD changes as it is more towards producing renewable energy from raw materials such as animal manure and food processing waste which is due to the high amount of water and degradable organic starch and cellulose [56]. The common concept of AD is compromised into four major steps, namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Regardless of what type of raw materials are used, the basic AD pathway will be implemented for all. In Malaysia, AD is executed through a series of open ponding system that is usually associated with POME that covers up to 85% of the biomethane plant while the remaining production plant uses an open digesting tank. The components involved in an open ponding system are de-oiling tanks, acidification ponds, anaerobic ponds, and facultative or aerobic ponds [55].

Furthermore, the capacity of the POME will determine the number of ponds needed for a particular production plant. The main concerning problem with using this system is the long retention time which takes up to 20–200 days [57]. Apart from that even with a high retention time, the open ponding system still promotes higher emission of methane with an average methane composition of 54.4% in comparison to an open digester tank. The suitability of using an open digester tank in Malaysia is only implemented during the limitation of land area that is available for the ponding system. In an open digesting tank, the retention time and the capacity needed in the plant are much lower compared to the open ponding method. But the methane emission from open digester tanks is still low with an average methane composition of 36.0%. The main problem of the low methane composition is mainly because of the transfer of oxygen into the tank when feed is induced into the tank. In a conventional digester tank, the impeller installed will improve the mixing that at the same time increases the contact of the raw material and bacterial consortia. But the mixing is highly dependent on the slow bubbling and eruption of biogas that leads to low conversion of methane gas [58].

Therefore, as a way to mitigate this issue, two-phase anaerobic digestion (TPAD) could be implemented. Incorporating TPAD into wastewater treatment has demonstrated its effectiveness by proving its increased stability and higher methane production rate compared to conventional anaerobic digesters [59]. However, to fully utilize the TPAD for beneficial output, the substrate characteristics must be known so that suitable parameters can be employed to achieve high-rate performance. Therefore, researchers should investigate the feasibility of optimizing POME properties that can be implemented into the TPAD system. In addition, Aziz et al., reinforced the fact that POME is the predominant feedstock for the industrial application of AD in Malaysia. POME is employed in lagoon systems (covered lagoons) and continuous stirred tank reactors (CSTR), also known as closed anaerobic digester tanks [51]. As discussed previously, covered lagoons are a more preferable alternative for Malaysia because of their low development costs. However, this results in a substantial carbon footprint. As a result, Malaysia is actively transitioning toward the use of CSTRs, which exhibit enhanced gas production due to the CSTR's mechanical agitator, which increases biomass contact area. In addition, the adoption of CSTR increases the proportion of methane in biogas to 62.5%. In Malaysia, 42% of biogas industries employ covered lagoons and 58% use anaerobic digester tanks for POME treatment, demonstrating the successfulness of CSTR [16].

4.2. Biomethane Plant in Malaysia. The increasing demand for biomethane has led to a total of 125 biogas plants that are fully operated in Malaysia, as recorded in December 2020. This contributes to 28% of nationwide biogas implementation and most of the biogas plant from the total biogas plant contributed to the national grid [58]. One of the emerging companies is BiON that is based on environmental technology and is located in Kuala Lumpur. In recent years, BiON has expanded its focus toward waste-to-energy through the development of biogas power plants that also act as independent power producers to generate renewable energy from the treatment of palm oil mill effluent (POME). Furthermore, other company such as FGV Holdings Berhad's (FGV) venture in a biogas plant for the national grid act as an alternative form of energy for TNB, which enhances the reduction of the risk of an outage to ensure a better and steadier stream of electricity. Since POME is known for its environmental pollutant, FGV had an integrated water treatment capacity that can improve the discharge quality into the nearby river. On the other hand, the POM is also equipped with a POME polishing plant to further increase the water discharge quality [60].

The project of biogas plant primarily is observed through Cenergi SEA Sdn Bhd which is one of the leading companies in the production of biomethane in Malaysia. Cenergi SEA Sdn bhd is a developing company that incorporates sustainable energy solutions that specializes in reducing carbon emissions through investment in renewable energy and energy efficiency projects, and several beneficial impacts have been brought through the executed projects from Cenergi such as 231 GWh electricity supplied to the National Grid Network, RM 59 million savings in energy cost from energy efficiency projects, and also up to 1,206,520 tonnes in carbon saving [61]. In terms of process flow in the Cenergi plant, firstly the processing of fresh fruit bunches (FFB) generates wastewater that is known as POME. This POME will act as a feedstock for biomethane production and also be utilized by anaerobic digestion to steadily produce biogas. This biogas consists of 60% of methane and 40% of carbon dioxide. The H_2S concentration on the other hand will be reduced from 3000 ppm to 150 ppm through bacteria activities or biological processes. The reason for the reduction to 150 ppm is to prevent corrosion and increase the lifetime of the biogas engine. After this stage, the biogas is led into a dehumidifier also known as a chiller. The biogas is rapidly chilled to less than 10°C and this removes moisture and thus achieving less than 50% humidity. This makes it easier for the biogas to combust. Then, the treated biogas flows through blowers and into the biogas engines where it will be combusted to convert into electricity. This electricity will be injected into the national grid. In case of engine shutdown, the biogas is flared. Therefore, this prevents the release of methane into the atmosphere through this environmental manner and also ensures the Cenergi plant produces a cleaner source of energy for all. The key features of the Cenergi biogas plant include several features such as longer wastewater retention time, lower methane emissions, higher biogas yield, and up to 90% COD removal efficiency. Apart from that, the volume of biomethane produced by Cenergi that is prevented from the release is also equivalent to over 9,600 tonnes of carbon dioxide [61].

In terms of the yearly production of biomethane in Malaysia, compromising all the biomethane plants is reported nearly 500 kt if all the POME is treated anaerobically. The gaining interest of the biogas market in Malaysia is more towards the conversion of biogas into renewable electricity such as Sungai Kerang Palm Oil Mill with a capacity of 211,475 m^3, Syarikat Cahaya Muda Perak with a capacity of 232,745 $m^{3,}$ and many other plants that are also invested in biomethane injection into natural gas grid [62]. Furthermore, based on the data provided by SIRIM Berhad, in Malaysia, there were around 400 palm oil mills that generate 71.5 million m^3 of POME yearly. Apart from that, another biogas plant involvement is the FBG biogas plant which also uses POME as the choice of feedstock and is located at Kedah Darul Aman [63]. The main perspective of this project is to elevate the biogas capture technology as it is derived towards the capture of the release of greenhouse gases mainly methane gas into the atmosphere and converts the gas into electricity using highly efficient biogas engine generators. Then, the electricity generated from the plant is supplied to nearby towns and villages under the Feed-In-Tariff (FiT) program. On 17 March 2018, the FRG biogas plant gained approval from Sustainable Energy Development Authority Malaysia (SEDA Malaysia) and the project is ready to start the Feed-in Tariff to the national grid at a bonus rate of 47 cents per kilowatt. Apart from that, there is also a collaboration between Camco South East Asia and the Palong biogas plant in Pahang state [51]. This collaboration's main purpose is to allow the Palong plant to implement the technology used by Camco which is through anaerobic digestion to recover methane-containing biogas from the effluent, which is then used to generate electricity. Figure 2 shows the utilization of POME by leading companies that produce biomethane in Malaysia.

5. Recent Studies of Biomethane Production in Malaysia

5.1. Biogas Capture. As mentioned in the previous section, the selection of POME as a renewable source of energy has some serious drawbacks. Therefore, to overcome this issue, Malaysia has developed attention to recovering the dissipated biogas by implementing biogas capture technology. Malaysian Palm Oil Board (MPOB) is the governing agency that derived the path of biogas capture in Malaysia whereby the first action is focusing on building biogas trapping facilities across palm oil mills (POM) that reflects towards national Entry Point Project (EPP) 5. According to Sari et al, in the palm oil industry, the Green House Gas (GHG) emission is estimated to be significantly lower by 17–20 million tons of CO_2 annually if Malaysia implements this biogas capture technology successfully [50].

The innovative method of capturing biogas in Malaysia that was developed by companies such as Weidasar engineering Sdn Bhd, Konzen Clean energy Sdn Bhd, and Smart & Green Sdn Bhd is through a continuous stirring device that is integrated with a closed anaerobic reactor. Apart from that, the modification of methane fermentation where the system can act either in mesophilic or thermophilic conditions was developed by MPOB with incorporation with Ronser Biotech Sdn Bhd [3]. These joint forces had developed the various options of reactor that is suitable for biogas capture and utilization such as expanded granular sludge bed (EGSB) and hybrid plug-flow system of up-flow anaerobic sludge beds (UASB). In this context, the details of how each technology serves towards biogas capture cannot be publicly disclosed [62]. However, all the important consideration needed for biogas capture from raw material like POME was fully considered such as loading and flow characteristics of POME in the digester, solid removal, reaction temperature, and hydraulic retention time (HRT), and also POME characteristics and quality. Table 4 shows the biogas capture technologies with the respective company in Malaysia.

According to Loh et al., these technologies' implementation has impacted the efficiency reduction of BOD and COD by 80–90% which achieved the goals of biogas capture as high BOD and COD will only cause an unfavorable condition in watercourses that leads to environmental pollution. The need for the development of biogas capture technology is to modify the inefficiency of the conventional methods which is through a covered lagoon system. In a covered lagoon system, the processing time is very slow that is mostly due to bacteria and substrate contact. Large capital investment is needed as the lagoon system requires a large footprint [2]. Furthermore, this system can only be specified to certain conditions like mesophilic and cannot be integrated into different conditions as the innovative method. Apart from that, the hydraulic retention time is up to 20–90 days which is not ideal for long-term production as it is one of the most important design parameters affecting the economic feasibility. Higher retention time will only lead to a low yield production rate that also requires higher energy consumption. Therefore, modified strategies which were mentioned in the innovative method are vital to meet the growing demand for biomethane in Malaysia [5].

In addition to biogas capture advancements, companies and organizations such as MPOB and Offshore Engineering Sdn Bhd (SDOE) have developed a biogas upgrading plant with a capacity of 400 m^3/h that utilizes membrane technology to remove carbon dioxide, resulting in a high methane production of more than 92%. Apart from that, through biomethane supply chain management, liquid biomethane can be used as an alternative to gaseous biomethane, which is also known as liquefied biogas and has a volume about 600 times less than its gaseous volume [64]. Furthermore, as discussed in the preceding section regarding the significance of carbon dioxide and sulphur dioxide removal for achieving a higher fuel standard for biogas development, mature technologies on biogas upgrading methods, such as physical scrubbing, chemical

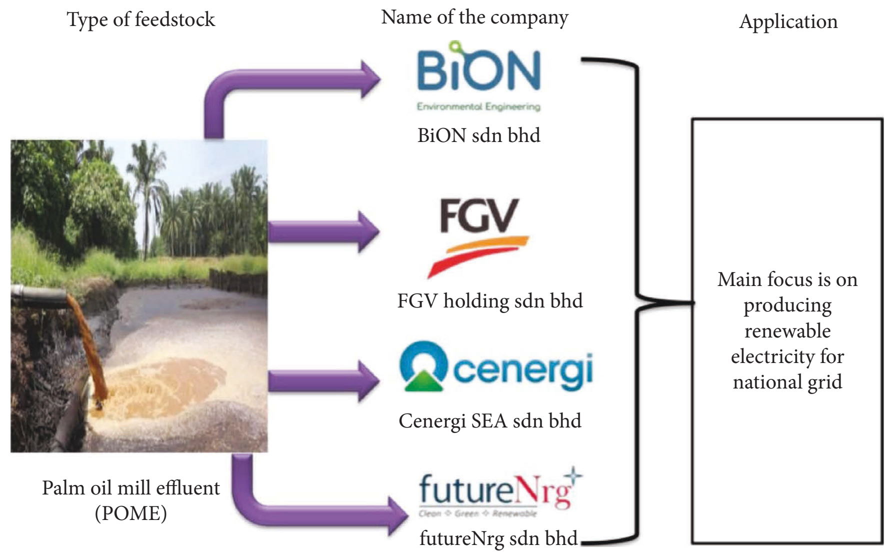

Figure 2: Utilization of palm oil mill effluent (POME) by leading companies that produce biomethane in Malaysia [35, 51, 60, 61].

Table 4: Biogas capture technologies with the respective company in Malaysia [2].

Name of the company	Type of system incorporated
Weidasar Engineering Sdn Bhd Konzen Clean energy Sdn Bhd Smart and Green Sdn Bhd	(i) Closed anaerobic reactor with continuous stirring
Malaysian Palm Oil Board (MPOB)	(ii) Expanded granular sludge bed (EGSB)
Ronser Bio-tech Sdn Bhd	(iii) Up-flower anaerobic sludge beds (UASB)
Veolia Water Solutions & Technologies Sdn. Bhd	(iv) Reversible flow anaerobic baffled reactor (RABR)
Kubota Corporation	(v) Submerged membrane reactor

scrubbing, pressure swing adsorption, membrane separation, and cryogenic separation, are attracting the interest of researchers because they can assist in enriching the methane content [1, 2]. For instance, one of the most recent studies conducted by Jusoh et al. incorporated membrane technology that was infused with *f* thin-film composite membrane consisting of Linde *T* and fluorinated polyimide, with the result that the membrane successfully removed more than 96% CO_2, thereby meeting the biomethane quality requirement for vehicle fuel use [65].

5.2. Potential application and Utilization of Captured Biogas. In terms of utilization of the captured biogas, there are many useful sources of energy that can be implemented in most applications as the captured biogas can be converted to renewable energy such as heat or electricity. As for the current status of the biogas captured in Malaysia, the main focus is derived on steam generation, downstream business activities, electrical generation, and even Combined Heat and Power (CHP) for the production of steam and electricity [5]. CHP refers to a technology that captures the wasted heat from generating electricity into useful thermal energy. Apart from that, based on the location of the biogas plant, the biogas can be captured for grid connection that can produce renewable electricity. One of the most common utilizations of captured biogas is used directly for heat and electricity generation that is specifically in Palm Oil Mill (POM). Firstly, the biogas captured during the palm oil milling process can be burnt together with the biomass of oil palm which exists in two forms, namely, mesofiber (MS) and palm shell (PS) in boilers. In order to achieve steam generation that is up to 75% thermal conversion efficiency, there must be adequate modification action to the boilers that allow proper feeding of the biogas into the chamber of the boiler [50].

Next, another potential application is that the captured biogas can act as additional power for other downstream processing that is within the area of the mill such as kernel crushing plant or even fiber processing plant [55]. The concept is implemented by associating with boilers whereby the electricity generated in the biogas plant from processing fiber is used internally for the production of boiler fuel and dry long fiber. Furthermore, biogas capture is also utilized for internal combustion engines, for instance, in diesel generators, the electricity that is produced is either used in the grid connection *n* grid or for internal consumption which also leads to the conversion efficiency of up to 42% [17]. Apart from that, the modification of the boilers in terms of the take, fuel settings, and also feeding will promote the reduction of diesel consumption by 70%. The implementation of these modified strategies can be observed in

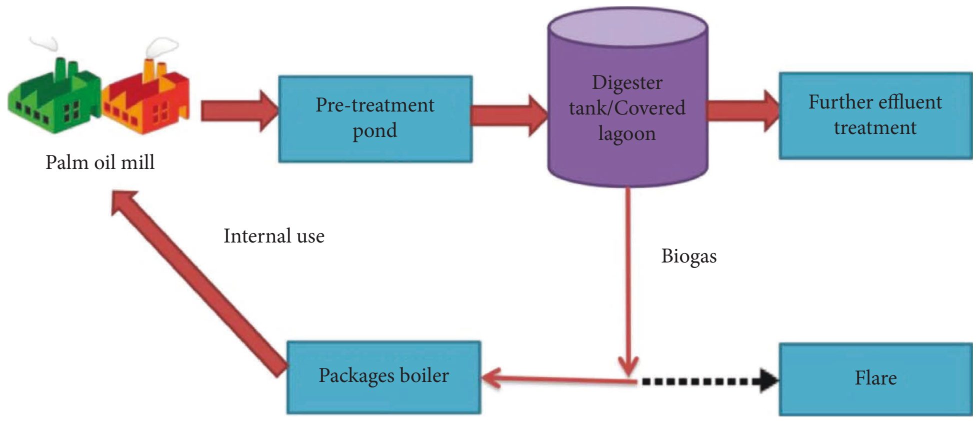

Figure 3: Process flow diagram for biogas captured and used in package boiler [2].

TeeTheh POM, Rompin, which utilize gas capture for electricity production and also for internal consumption. On the other hand, Keck Seng (*M*) Sdn Bhd, Johor utilizes biogas capture by integrating it as partial replacer fuel in their package boilers. This utilization reduces the dependence on limited resources such as natural gas and fuel oil [66]. The main goal is to achieve efficient thermal generation by 80% through firing the biogas from POME in the package boiler to produce heat or steam. Figure 3 shows the process flow diagram for biogas captured and used in the package boiler.

6. Government Strategies and Policies

6.1. Life Cycle Assessment (LCA) in Biomethane Production. The term "life cycle assessment" refers to a systematic examination of products or services' possible environmental consequences throughout their entire life cycle, from raw materials to processing, production, distribution, usage, and disposal or recycling. Thus, the implementation of LCA in a biomethane plant is significant because it may be used to avoid lowering environmental impact at one point of the life cycle while raising it at other phases [67]. Apart from that, LCA gives a comprehensive perspective of environmental consequences and may be used to prevent optimizing one environmental metric without taking into account the implications on other indicators [24]. Furthermore, LCA allows for the identification of environmental impact hotspots as well as the assessment of how to modify processes to decrease environmental impacts [68]. Goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation are the four phases of LCA. In the production of biomethane, LCA may also be applied to analyse environmental impacts associated with a product, process, or service by determining the energy required, materials utilized, and emissions discharged into the environment. Environmental impacts may be measured at the end of the cause-and-effect chain in LCA. As a result, the LCA technique may be used to identify possibilities to enhance a system's environmental performance. An LCA-based environmental assessment, on the other hand, is an integrated method that can demonstrate that biogas generation is a clean and safe technology [67]. Furthermore, LCA is a cradle-to-grave strategy to analyse a product's impacts over its whole life cycle, from raw material extraction to production, manufacturing, transportation, usage, and the management of the discarded product, whether through recycling or final disposal [51]. Composting of digestate from the biomethane production as well as the treatment of biologically processed effluent using natural coagulant should be considered to ensure the sustainability of the process [69, 70]. Therefore, as an overall approach, LCA is a fundamental tool that should be applied in biomethane plants to evaluate the environmental performance of the biomethane produced.

6.2. Malaysia Biomethane Target-Power generation. Malaysia, as a tropical country, has an abundance of biomass resources. Aside from residues produced by the palm oil industry, biomass may be obtained from the production of sugar cane, rice, maize, and coconuts, as well as municipal trash and manure from agriculture. The government resolved to speed up the development of the biogas sector to make use of these resources and make use of Malaysia's projected biogas potential of more than 500 MW. For example, the EPP5 program aims to equip a biogas plant in every palm oil mill by 2020 [4]. This means that the environmental pollution caused by the disposal of sewage created by palm oil production would be reduced. Additionally, all palm oil mill owners want to expand their business by adding other mills and installing a biogas plant. Despite this, only 35% of palm oil mills have a biogas plant installed [17]. Furthermore, biogas production might help palm oil producers by making it easier to obtain certification for sustainably produced palm oil. The feed-in-tariff (FiT), which allows the producer of renewable energy to feed the generated renewable energy into the network of the national grid operator TNB for 16 years at a set price, is known as a tangible tool for accelerating the growth of the biomass and biogas industry. However, the growth of the biogas industry has not been as successful as that of Thailand which is our neighboring country, whereby the biomass resources are used to generate more than 7% of electricity [5]. One reason is that the amount of additional capacity that can be added each year is restricted. Furthermore, unlike Germany, there is no structure in place that prioritizes the use of renewable energy. Malaysian biomass, on the other hand, is utilized to make pellets, bio-fibers, and Bio-CNG, which are then sent to Eastern Asian markets. While international business delegations are increasingly looking into Malaysia's bioenergy potential, local players see biogas use as more of a difficulty than an opportunity. As a result, the majority of biomass is burnt or disposed of in the environment [22]. Therefore, further improvement and development of biomethane plants are essential to elevating the potential of biogas in the industry in Malaysia.

7. Conclusion and Perspective

In conclusion, the production of biomethane is beneficial as it eliminates the release of methane gas and other harmful gases and also reduces the need for fossil fuels which further reduces the emissions of greenhouse gases into the atmosphere. Not only that, biomethane production brings a positive impact on nonenergy sectors. They are generated from different types of organic residues, turning waste into a valuable resource, which also helps in developing the economy. Since Malaysia is in a tropical area and has a lot of resources for organic matter needed to produce biomethane, the government should accelerate the expansion of its biomethane activities. In order to generate biomethane in Malaysia that is not solely driven by POME, more study is required to identify additional bioresources. POME is commonly used in the majority of Malaysian biogas plants, in part because it is simple to convert liquid to biomethane gas. The research on the suitability of the bioresource for biomethane generation should be addressed because Malaysia has a variety of bioresources, most of which are in solid form. This can be accomplished by implementing suitable methods for handling raw materials in solid form.

In addition, before implementing anaerobic digestion, solid waste management is one of the future prospects for biogas development in Malaysia that requires greater attention. Prior to disposal into landfills, waste needs to be separated from inorganic waste at the source, which makes it easier for the waste to be digested anaerobically and greatly lowers greenhouse gas emissions. Additionally, it is anticipated that efficient waste segregation will result in the production of 60 Mm^3 of biogas, which is comparable to a potential 16.3 MW of power. Aside from that, the adoption of advanced technology for local biogas plants from other countries requires technical competence, thus the production of biogas from various sources can only be accomplished with the cooperation and participation of all parties, including the government, the private sector, and individuals. Moreover, further study should be carried out to further optimize the performance of anaerobic digester that suits the characteristics of the locally produced waste that is utilized for biomethane production. This is due to the nature of the technology itself which is known as feedstock-sensitive technology that necessitates the need of customizing the anaerobic digester before the overall production process begins. Not only that, in order to make biomethane economically competitive in the Malaysia market, government needs to control and not heavily subsidized on fossil fuel consumptions.

As indicated throughout this review, Malaysia should maximize its potential as one of the world's largest palm oil producers, not only to meet the growing demand for palm oil, but also to promote the growth of POME, a by-product of palm oil production. On the basis of the Malaysian biogas plant, it can be determined that the renewable energy produced is primarily derived from the national grid. Malaysia should therefore develop a strategic plan to increase the potential for producing renewable electricity. Collaboration with Tenaga Nasional Berhad (TNB) is one of the options that might be adopted. This collaboration would allow the high potential of the electricity produced through biomethane production to be purchased and utilized by TNB as a contingency source of electricity. Moreover, the construction of biomethane injection infrastructure will also well develop through this collaboration. On the other hand, collaboration with companies from developed countries such as Japan, Germany, and Poland will enhance the implementation of more modernized technologies with a shorter retention time, applicability in various conditions such as mesophilic and thermophilic, and a higher methane content. Additionally, this development will serve as an added benefit for Malaysia, particularly for rural residents who have difficulty establishing adequate electricity.

As stated previously, the majority of landfills in Malaysia utilize anaerobic digesters to handle the collected waste. Therefore, the anaerobic digester can be outfitted with additional technological components for the advancement of biogas capture. Since the majority of biomethane plants use POME as a raw material, a policy should be developed to preserve the quality of POME. In a biomethane plant, for example, there are multiple open ponds for the collection of POME, which implies that different ponds will have varied concentrations and qualities of POME, which may also be affected by external factors such as the weather on rainy days. Consequently, this policy will verify the POME in a standardized manner with the same quality and concentration, which is crucial for preventing manufacturing plant disruptions. This can be accomplished by installing a POME mixing pit, which ensures that the feed entering the anaerobic digester has the same standard POME composition. In essence, the continued development of biomethane production is crucial for the future and expansion of Malaysia's economy.

Data Availability

All the data are provided in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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