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LIGNOCELLULOSIC BIOMASS-DERIVED BIOGAS: A REVIEW ON SUSTAINABLE ENERGY IN MALAYSIA

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ABSTRACT

Lignocellulosic Biomass (LCB) is regarded as a potentially sustainable alternative resource to fossil fuels. To address concerns related to environmental degradation and geopolitical tensions arising from resource scarcity, the global focus shifted towards developing and utilising sustainable and Renewable Energy (RE) technologies. Biogas technology has attracted attention due to its promising potential to generate energy from agro-waste and the preservation of natural resources. Therefore, this review explores the potential of utilising RE, specifically focusing on its practical implementation in Malaysia. It critically evaluates pre-treatment methods suitable for the country's prevalent biomass sources, offering insights into their applicability. Additionally, the article provides updated data on Malaysia's strategy to advance RE production, particularly in biogas. Despite considerable efforts, there is a notable gap in comprehensively assessing the impact of pre-treatment methods on LCB in Malaysia's biogas production. Hence, this article critically assesses recent advancements to address this gap, focusing on potential challenges and the comparative effectiveness of treatment techniques in Malaysian biogas production. It is with the aim to shed light on associated drawbacks and suggest means to enhance performance. Finally, this article ends by reviewing economic analyses for pre-treatment in LCB, focusing on efficient biogas production.

Keywords: agricultural waste, anaerobic digestion, biogas production, lignocellulosic materials, sustainable energy.

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INTRODUCTION

The global population's continued growth remains a significant driver of increasing energy demand in conjunction with societal and economic progress. Traditional fossil fuels, including natural gas, oil and coal, are the primary energy sources globally. However, their sustainability over the long term is questionable, especially for nations lacking fossil fuel reserves (Holechek *et al*., 2022; Hossen *et al*.,

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2016). Renewable Energy (RE) sources have gained prominence in recent years, thus, amplifying the need for sustainable energy sources and the imperative to reduce Greenhouse Gas (GHG) emissions. This aligns with the objectives of the 2015 United Nations Conference on Climate Change, the Paris Climate Agreement and the 2030 Framework for Energy and Climate (European Commission, 2016). Furthermore, one of the latest policy developments in this domain is the European Union's (EU) revised Renewable Energy Directive (RED II) implemented in 2021, which aims to increase the target for resource consumption to 32% by 2030. Moreover, EU member states must also ensure that at least 14% of energy used in their road and rail transport is derived from renewable sources by 2030 (European Commission, 2023).

Bioenergy has risen to become the fourth most common energy source in the EU since 2015, trailing only nuclear energy, hydropower, geothermal, wind, solar, and fossil fuels. The European Biomass Association (2017) reported that bioenergy accounted for an impressive 130,200 kilotons of oil equivalent (ktoe). This has significantly surpassed energy generated from water sources (29,327 ktoe, *i.e.*, 14.30%). The recovery from the COVID-19 pandemic and the global responses to the energy crisis have resulted in a significant upsurge in global investments in clean energy. Additionally, the International Energy Agency (IEA, 2023c) has reported that the projections indicate that approximately USD2.8 trillion will be allocated to energy investments in 2023. Of this total, over USD1.7 trillion is earmarked for clean energy, encompassing sectors such as renewable power, nuclear energy, grid enhancements, energy storage, low-emission fuels, efficiency enhancements, and the expansion of end-use renewables and electrification. In contrast, over USD1.0 trillion is dedicated to unabated fossil fuel supply and power. Within this allocation, about 15% of the funding is directed towards coal, with the remaining portion allocated to oil and gas. This marks a significant shift, as for every USD1.0 invested in fossil fuels, a substantial USD1.7 is now being directed towards clean energy initiatives. It is noteworthy that this ratio was at parity just five years ago, with fossil fuels and clean energy receiving equal investment (IEA, 2023c).

In 2023, modern bioenergy which encompasses biogases, liquid biofuels, and solid bioenergy, already constitutes more than 50% of the global RE demand. Forecasts indicate that, by 2030, the combined installed capacity of all renewable power sources will be more than double in both the Stated Policies Scenarios (STEPS) and the Announced Pledges Scenario (APS) (IEA, 2023d). Remarkably, in the Net-Zero Emissions (NZE) scenario, the installed capacity of RE sources is set to triple by 2030. This represents a significant milestone in the collective effort to achieve the ambitious 1.5°C global temperature goal, emphasising the crucial role of RE expansion in this endeavour (IEA, 2023b). Moreover, we have witnessed consistent growth in the use of biomass as a sustainable energy source in the energy sector. This is attributed to various factors, including increased government initiatives for sustainable energy technologies, the demand for alternative energy sources, reduced emissions, and the vast untapped potential of biomass. However, the solar Photovoltaic (PV) and wind energy sectors are poised for remarkable future growth, particularly within the power industry (IEA, 2022; Jones & Olsson, 2017).

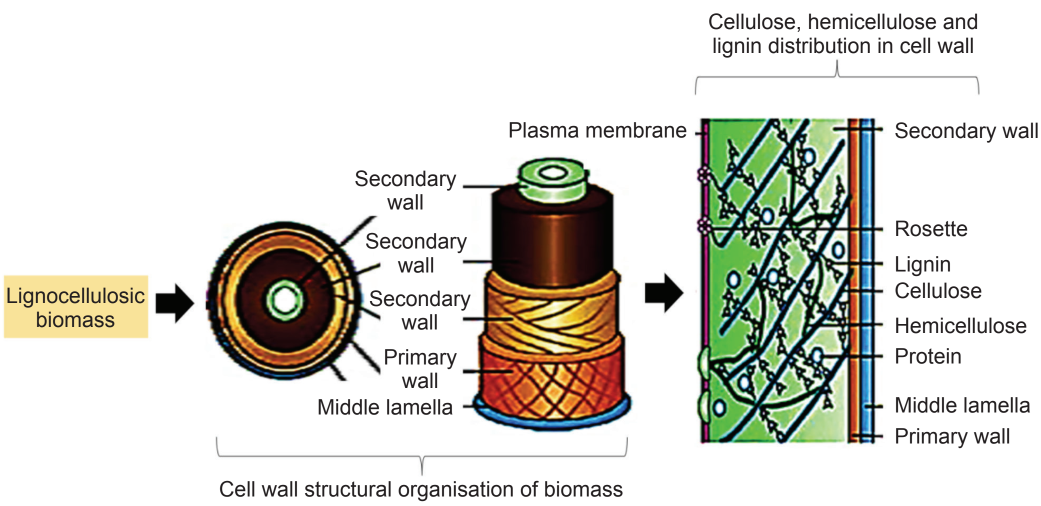
Malaysia, endowed with favourable climate conditions for agricultural production and dense tropical rainforests, are conducive to timber activities, which generates abundant biomass waste annually. The conversion of biomass into environmentally friendly energy and value-added products has been a focus of attention in Malaysia for several decades (Chan & Chong, 2019). Notably, the biomass waste generation in Malaysia is approximately 168 million tonnes (Zafar, 2022), with most of it comprising agricultural waste (90%), followed by municipal waste and forest residues. As a prominent agricultural commodity producer within the Association of Southeast Asian Nations (ASEAN) region, Malaysia is strategically positioned to advocate for and leverage biomass as a RE source. Accordingly, industrialisation which created the biomass industry in the 1900s, has led to the discovery of the vast potential economic benefits of biomass (Yatim *et al.*, 2017).

Lignocellulosic Biomass (LCB), recognised for its potential in addressing challenges posed by fossil fuels, especially coal, is a significant contributor to environmental degradation and is acknowledged for its sustainability and minimal carbon dioxide (CO_2) emissions. Furthermore, it boasts a heating value equivalent to energy crops, while producing no pollutants (Benti *et al.*, 2021). Biomass currently holds a significant position within Malaysia's energy composition. However, it still has yet to fully realise its potential, primarily due to uncertainties in biomass supply and various technical, financial, and policy-related obstacles (Rashidi *et al.*, 2022). The utilisation of biogas, primarily sourced from municipal solid waste, food waste, cattle manure, sewage, and palm oil mill effluent (POME), presents substantial prospects. With a potential capacity of approximately 2.3 gigawatt (GW), biomass stands as the most abundant resource in Malaysia, distributed across Peninsular Malaysia (1.3 GW), Sabah [561 megawatt (MW)], and Sarawak (448 MW). Furthermore, biogas and municipal solid waste exhibit promising potential, with a combined capacity of 736 MW and 516 MW, respectively [International Renewable Energy Agency (IRENA), 2023].

Figure 1 presents the three main interwoven constituents of polymers that make up the LCB. Reports have revealed that cellulose constitutes the major part, of about 40%-45%, hemicelluloses from 25%-35%, while lignin made the remaining 20%-30% (Bhatia *et al.*, 2019; Yogalakshmi *et al.*, 2022). In addition, these biomasses contain a minor amount of extractives such as starch, lipids, resins, proteins, fats, simple sugars, fatty acids, phenolics and essential oils (Pattiya, 2018; Pecha & Garcia-Perez, 2020). These ingredients are indiscriminately dispersed along the cell wall as a skeletal arrangement, merging rigid solids and elements, respectively. Typically, cellulose clumps into pertinacious fibres and builds a skeletal structure along the cell wall. At the same time, the inner voids are loaded with lignin and hemicelluloses, functioning as connectors. Lignin and hemicellulose components link with cellulose via a hydrogen bond, while hemicellulose and lignin constituents are covalently and hydrogen-bonded, influencing biomass's pyrolysis properties. Several reports have suggested the potential of LCB to produce biogas (biomethane and biohydrogen) alongside the various treatment techniques for optimal performance (Kainthola *et al.*, 2019; Kim *et al.*, 2015; Koupaie, 2018; Ma *et al.*, 2019; Matheri *et al.*, 2018; Phuttaro *et al.*, 2019).

This article extensively explores the potential for generating RE from LCB, particularly highlighting its effective utilisation within Malaysia. Focussing on tropical countries like Malaysia, where agriculture significantly contributes to the national economy [Abu Dardak, 2022; International Trade Administration (ITA), 2022], this article underscores the importance of optimising biomass resources. Furthermore, biogas production using biomass has been extensively discussed and reviewed in Malaysia due to its widespread availability and efficient conversion potential. RE, particularly biogas, has garnered significant attention globally, with concerted efforts by governments to maximise the utilisation of biomass resources. Rashidi *et al.* (2022) conducted a comprehensive review focusing on biomass utilisation as an energy source. Their work examined the future growth of the biomass energy market in the country and emphasised effective implementation to address poor disposal issues while creating employment opportunities. Simultaneously, Aziz *et al.* (2019) conducted a comprehensive analysis employing the Life Cycle Assessment (LCA) methodology to evaluate the environmental performance of biogas generation, reflecting a collective effort towards understanding its ecological impact.

While various reviews have encompassed biomass utilisation in general, this article specifically centres its scope on LCB prevalent in Malaysia. This includes palm oil mill waste, sugarcane bagasse, corn stover and rice processing waste. It critically evaluates pre-treatment methods tailored for these specific lignocellulosic substrates, reflecting their suitability for implementation in Malaysia. This article also offers the most recent updates and current data concerning Malaysia's strategy and plan for enhancing RE production, specifically focusing on biogas. Despite considerable efforts, there remains a significant gap in comprehensive evaluations concerning the impact of pre-treatment methods on LCB in Malaysia's biogas production. Thus, to address this gap, this paper aims to critically assess recent advancements, focusing on the potential, challenges, and comparative effectiveness of various treatment techniques used in Malaysia's biogas production. The review aims to shed light on associated drawbacks and provides suggestions



Source: Tiwari *et al.* (2023).

Figure 1. Major polymeric constituents are present in lignocellulosic biomass.

for enhancing performance. Additionally, it delves into an economic analysis of pre-treatment methods specifically tailored for LCB in biogas production, hence offering insights into economic feasibility.

SUSTAINABLE ENERGY AND LIGNOCELLULOSIC BIOMASS UTILISATION IN MALAYSIA

Sustainable and Renewable Energy in Malaysia

Several studies have reported the assessments and analyses of Malaysia's evolving energy policy and strategies. These include Malaysia's sustainable energy (Basri *et al.*, 2015), Malaysia's sustainable power generation plan up to 2030, Malaysia's green RE policies and programmes, RE policies and initiatives for a sustainable energy future and the selection of energy sources for long-term electricity generation. These programmes and initiatives include an elaborate review of pre-treatment methods for LCB (Ahmad & Tahar, 2014). However, the recent issues regarding the high production of agricultural wastes rich in lignocellulose in Malaysia have generated some concerns. It is acknowledged that Malaysia generates a significant amount of agricultural waste, with an estimated 1.2 million tonnes produced and disposed of each year. Unfortunately, some of these wastes are improperly disposed of, through open burning or decomposition, hence increasing environmental problems (Sarangi *et al.*, 2023).

Malaysia is currently experiencing rapid urbanisation, and the population expansion is expected to rise to 37.4 million by 2030. This country is rich in natural energy resources and has been relying on fossil fuels, including oil, natural gas and coal, as its primary energy sources for a long time (Oh *et al.*, 2018). Its energy reserves had 4.553 billion barrels (bbl) of crude oil, 79.531 trillion cubic feet (Tcf) of natural gas, and 1,938.37 t of coal as of January 2018 (Zulkifli, 2021). Since fossil fuel resources are hard to be replenished quickly to meet the demands of such persistent consumption, the Malaysian government has been promoting RE since 2001, as a greener alternative using hydropower, biomass, and solar. However, the excessive utilisation of fossil fuel resources and the underutilisation of RE has since resulted in environmental pollution, climate change, and global warming (Oh *et al.*, 2018). Therefore, the Malaysian government has now shifted its paradigm towards sustainable, reliable and environmental-friendly energy sources. The government and critical stakeholders have embraced the need to diversify the fuel mix, which will serve as a stepping stone for enacting a policy on national energy security (Dharfizi *et al.*, 2020). In 1979, Malaysia's National Energy Policy was established for a much affordable and efficient energy usage (US Energy Information Administration, 2020). Subsequently, the government has consistently implemented several energy policies, targeting energy security (Lim & Goh, 2019), specifically gas, coal and oil. Accordingly, these efforts sought to lessen the overdependence on fossil fuel-based energy sources by increasing renewable energy as an alternative energy source.

It was later followed by the gazettement of the Renewable Energy Act (REA) in 2011, together with the Feed-in Tariff (FiT) strategy and the launching of Incentive-Based Regulation (IBR) in 2014. Moreover, the National Energy Efficiency Action Plan (NEEAP) was introduced into the Malaysian Action Plan from 2016 until 2025 to focus on sustainable energy usage under the 11th Malaysia Plan (2016-2020). A new Energy Efficiency and Conservation Act (EECA) have also been established to initiate early steps in reducing GHG emissions. The government's current goal for fuel diversification is to keep the Herfindahl-Hirschman Index (HHI) below 0.5 by 2025 to enhance energy security (Abdullah *et al.*, 2019). Recently, in 2021, Malaysia aimed to be a carbon-neutral nation (Bernama, 2021), with critical stakeholders such as Commerce International Merchant Bankers Berhad (CIMB) Group Holdings Berhad initiated its commitment to exempting coal from its portfolio by 2040 (Lo, 2020). Furthermore, Petroliam Nasional Berhad (PETRONAS), Malaysia's national oil company (Harun, 2021) and Malayan Banking Berhad (MAYBANK) aspired to achieve net-zero carbon emissions by 2050 (Greenpeace Southeast Asia, 2021).

By 2050, Malaysia anticipates that nearly one-fifth of its fuel demand will be sourced from renewables in the 1.5°C Scenario (1.5-S), encompassing bioenergy, renewable direct-use (*e.g.*, solar thermal), and hydrogen, which is a considerable shift from the current 1%, aiming to reach 70% of renewables in the power mix (EnerData, 2023; IRENA, 2023). A projected 40% of final energy consumption will be from electricity, meeting the increased demand for powering transportation and green hydrogen production. As of the end of 2021, Malaysia's grid was connected to a total installed electricity generation capacity of 33 GW. Coal and natural gas-fired power plants have constituted approximately a third of this capacity, while the remainder is comprised of a mix of large and small hydropower resources, biomass, and solar PV (IRENA, 2023). Over the last decade, the IRENA and the IEA reported that fossil fuels constituted around 95% of Malaysia's energy mix (IEA, 2023a; IRENA, 2023). As of 2020, Malaysia's national Total Primary Energy Supply (TPES) was primarily driven by four key energy sources. The largest share was natural gas, at 42.4%, followed by crude oil and petroleum products at

27.3%, with coal contributing 26.4% to the energy mix. Renewables, which include hydropower, solar and bioenergy, accounted for a minor portion, representing only 3.9% of the overall energy supply [Ministry of Economy (MoE), 2023].

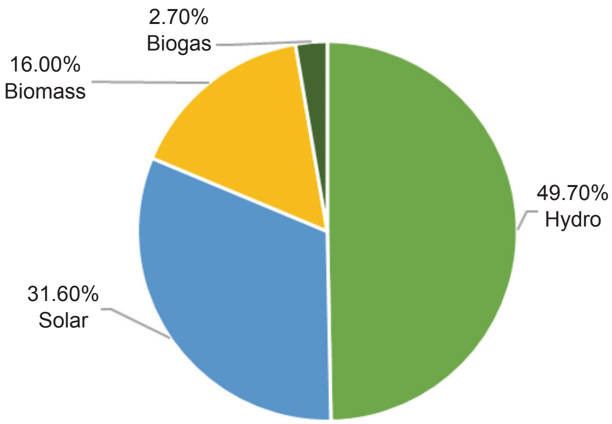
Transitioning to 2023, IRENA's findings highlighted that renewables now constitute a modest 5% of Malaysia's energy composition, mainly attributed to hydropower and solar sources (IRENA, 2023). Malaysia's commitment to low-carbon development is reflected in the National Energy Transition Roadmap (NETR), aiming to reshape the economic landscape towards sustainability. NETR focuses on accelerating the energy transition by shifting from fossil fuel-based to greener and low-carbon energy systems. Furthermore, projections exhibit a marginal annual energy demand increase, with notable initiatives to reduce reliance on fossil fuels, phasing out coal and enhancing dependence on renewable sources such as solar, hydro and bioenergy. The plan includes 50 initiatives under six energy transition levers, five enablers and flagship projects announced in 2023. It also intends to support the nation through a combination of financing methods (MoE, 2023). The successful implementation of the NETR is anticipated to boost Gross Domestic Product (GDP) and job creation significantly. This has highlighted a vision that extends beyond achieving net-zero GHG emissions, aiming to fundamentally transform Malaysia's economy for a more resilient and robust future.

The 12^{th} Malaysia Plan (RMK-12) recently introduced sets of an ambitious objective for the nation to achieve NZE by as early as 2050. This goal necessitates the incentivisation of clean energy adoption, the encouragement of enhanced energy efficiency, and the overall reduction of GHG emissions. The Hydrogen Economy has been expressly recognised as a key component in advancing green growth to attain Low-Carbon Nation status, particularly in the transportation sector. The facilitation of the RE industry's growth is accomplished through the implementation of the National RE Policy and Action Plan. This includes the execution of the Fuel Cells Roadmap and Hydrogen Roadmap for Malaysia (2005-2030), focusing on hydrogen generation from RE resources and the establishment of hydrogen networks for hydrogen fuel cell vehicles. The government has initiated a hydrogen energy roadmap to harness energy from hydropower resources in the state of Sarawak, which is naturally rich in hydropower resources [Minister of Science, Technology and Innovation (MOSTI), 2023].

The availability of biomass could eventually generate approximately USD4.4 billion in economic value annually, by presuming 30% accessibility with RM500/t value creation (Chan & Chong, 2019). Therefore, biomass retains the more significant proportion of 35%, outrunning the highest solar PV portions, with 11% recorded in 2014 by the Sustainable Energy Development Authority (SEDA) Malaysia (2021). This enormous abundance is usually left to decay as mulches or directly combusted as boiler fuel. Moreover, this tradition undermines the potential of lignocellulosic wastes to be recycled in a biorefinery to produce several value-added products, particularly RE and biochemicals (Yatim *et al.*, 2017). Notably, in 2021, the Ministry of Energy and Natural Resources of Malaysia (KeTSA) has established a target, aiming for a 31% share or 12.9 GW of RE in the national installed capacity mix by 2025, followed by 40% and 70% by 2035 and 2050, respectively [Malaysian Investment Development Authority (MIDA), 2023; SEDA, 2021a]. This ongoing evolution in Malaysia's energy strategy has underscored the country's commitment to diversifying its energy sources and expanding the role of renewables within its energy matrix. In 2022, Malaysia's GDP has surged to RM1,510.9 billion, marking an 8.7% increase from RM1,390.6 billion in 2021. The agriculture sector demonstrated a slight 0.1% growth in 2022, compared to a 0.1% decline the previous year, contributing 8.9% of the percentage share to the GDP of ASEAN countries [Department of Statistics Malaysia (DOSM), 2023].

Potentials of Agricultural Wastes for Biogas Production in Malaysia

Malaysia has a wide variety of agricultural wastes, including poultry waste, animal manure, sugarcane bagasse, rice husk, palm oil waste, and kitchen waste. It can be utilised for biogas production via Waste-to-Energy (WTE) to unravel the waste disposal challenges and energy exigencies of the country (SEDA, 2021b). SEDA Malaysia is responsible for implementing FiT and Net Energy Metering (NEM), together with the Energy Commission and Tenaga Nasional Berhad (TNB), for the Large Scale Solar and Large Hydro program, respectively (SEDA, 2021a). In November 2021, the initiation of a Green Electricity Tariff allowed individuals to choose electricity sourced from renewable resources by paying an extra fee per kWh. Subscribers participating in this program can also obtain a RE certificate (Aziz, 2023). Due to the efforts of these agencies, total RE capacity has grown tremendously, up to 8.2 GW in 2019 from 3.7 GW in 2012 (Hussin & Energy Watch, 2021). As of November 2021, the total installed capacity has vastly grown from 101.73 MW in 2012 to 661.22 MW under the FiT program. Resource types from these programs are solar PV, biogas, small hydro and biomass. The current share of biogas sources is 18% (119.74 MW), the second largest contributor after solar energy (387.03 MW) in electricity production from RE in Malaysia, followed by small hydro (83.8 MW) and biomass (70.65 MW) resources (SEDA, 2014). POME is the primary feedstock, with over 93% of the biogas production, followed by the organic landfill waste, which accounts only for 5%. *Figure 2* presents shares of the installed capacity (Energy Commission, 2023) from all mentioned RE sources in Malaysia, out of the total installed capacity of 9.04 GW, up to the end of 2022 (Bhambhani, 2023).

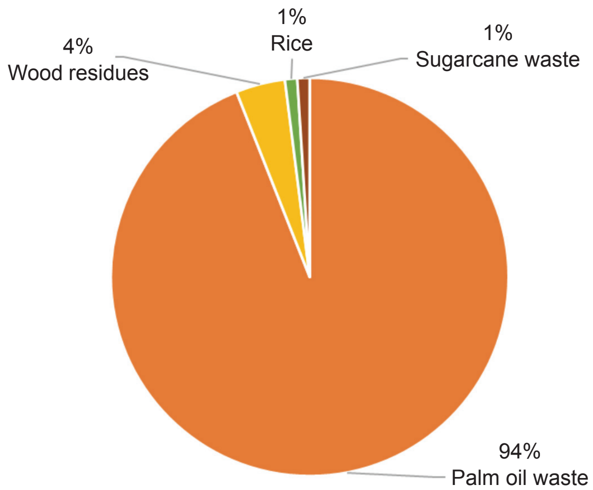


Source: Energy Commission (2023).

Figure 2. Shares of RE installed capacity for electricity generation in 2022.

Biogas production from agro-wastes has tremendous potential as an alternative source that can mitigate the utilisation of conventional fuels and significant global warming (Ardolino & Arena, 2019). Also, electricity production from biogas around the world is anticipated to rise from 331 terawatt-hours (TWh) in 2010 to 1,487 TWh by 2035, demonstrating growth from 8.0% of the total electrical energy produced from RE sources, which will rise to 13.0% by the year 2035. The EU drives the world to generate electricity from biogas by producing 61 TWh (Scarlat *et al.*, 2018). China forged 15.8 billion cubic meters (BCM) of biogas, substituting 5% of total natural gas and 11 t of coal in 2015 (Xue *et al.*, 2019). In Malaysia, researchers have analysed the impact of WTE policies on energy, economic and environmental factors. Based on their findings, Anaerobic Digestion (AD) is deemed as the most viable option for electricity production, compared to alternatives like gasification, landfill gas and municipal solid waste incineration (Tan *et al.*, 2015). The oil palm industry has been highlighted as one of the reliable biogas resources due to its expanding plantation area, around 5.67 million hectares in 2022 [Malaysian Palm Oil Board (MPOB), 2023b]. It covers approximately 17.2% of Malaysia's total land area of 33.02 million hectares (Sahabat Alam Malaysia, 2020). Hence, utilising resources from the oil palm industry for biogas production can aid in achieving the country's RE targets and promote sustainable waste management practices.

Malaysia has become one of the world's most crucial biofuel technology producers (Rezania *et al.*, 2020). On the other hand, agricultural wastes such as rice husks, wood, coconut stem fibres and biodegraded oil palm waste [such as empty fruit bunch (EFB)] can also become suitable substrates for biogas production. These wastes account for 168 t of biomass produced yearly in Malaysia and can be a viable alternative to fossil fuels (Wu *et al.*, 2017). Other agricultural produce, such as rubber, rice and other palm oil products (such as palm fronds, palm tree trunks and palm kernel shells), also have the potential to be utilised as biofuel sources (Su *et al.*, 2022). In 2019, various agricultural waste feedstocks for biogas production in Malaysia were observed, with POME identified as the most extensively used feedstock, accounting for 93%. The other sources included minimal quantities of manure (<1%), bagasse (<1%), landfills (5%), and sewage (<1%) (Lim *et al.*, 2021). In contrast, by 2023, as reported by the MOSTI, Malaysia's annual biomass waste production amounts to a minimum of 168 t. Palm oil waste is a primary constituent, representing 94% of the biomass feedstock. In comparison, *Figure 3* shows the remaining percentage which originates from agricultural and forestry by-products such as wood residues (4%), rice (1%), and sugarcane industry wastes (1%) (MOSTI, 2023).



Source: MOSTI (2023).

Figure 3. Biomass feedstock in Malaysia.

Similarly, animal manure has a high potential to be utilised as feedstock for biogas production in Malaysia. More manure waste is being produced since livestock farming keeps expanding due to the growing demand for dairy, beef, and chicken products (Abdeshahian *et al.*, 2016). However, it poses harmful environmental threats to the ecosystem and surroundings (Kumaran *et al.*, 2015). For instance, Gopinathan *et al.* (2018)

reported that most local farmers either dispose of their livestock wastes directly into the river or pile it up for natural decomposition, prior to being used as bio-fertilisers. Hence, using this waste for biogas production by deploying AD can also result in waste management to address the issue of odour and pathogens. In addition, sugarcane bagasse, composed of 50% cellulose, 25% hemicellulose and 25% lignin, is obtained from the fibrous residue of sugarcane after the juice extraction, can also be used as biogas substrates (Faizal *et al.*, 2019). In 2020, sugar cane production was reported to be almost 23,383 t in Malaysia (Knoema, 2021) and is processed into sugars and beverages, leaving a substantial amount of bagasse in the environment, with potential for biogas utilisation.

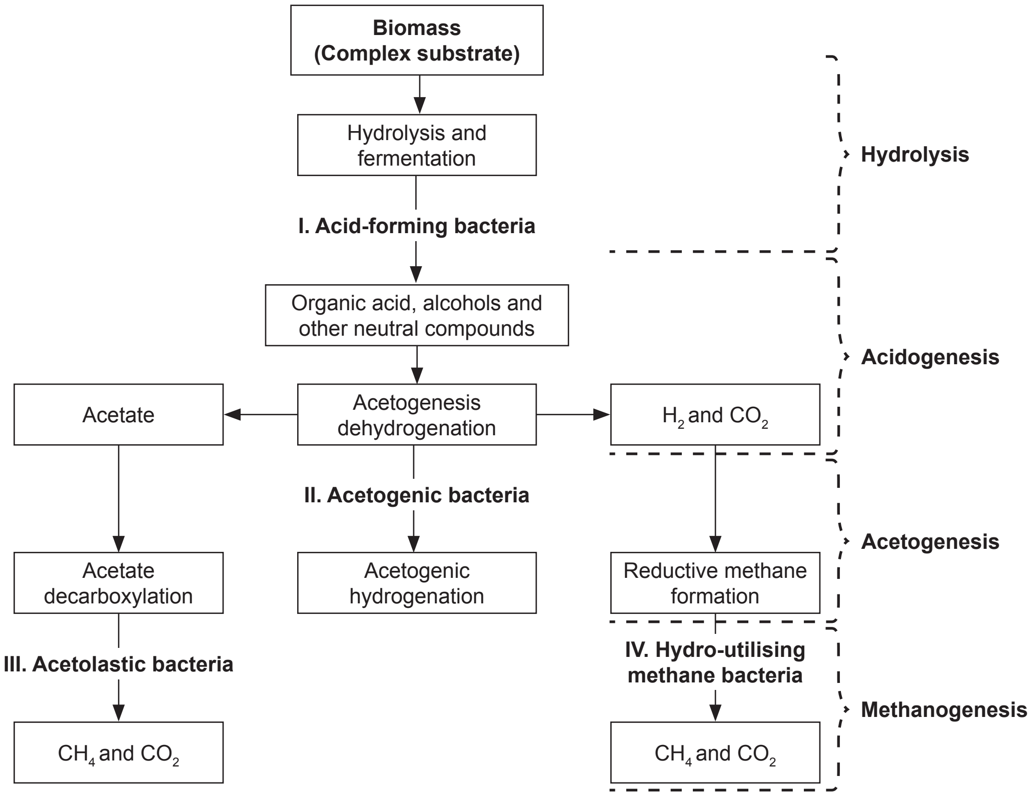
Biochemical Processes of Lignocellulosic Biomass Utilisation

As mentioned in the previous section, biogas has immense potential to be a cost-effective, growth-oriented, and environmental-friendly alternative energy source to generate electricity (Chien Bong *et al.*, 2017). It could be obtained from the biological breakdown of organic substances that contain 40%-75% methane (CH_4), 15%-60% CO_2, and trace amounts of hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen (N_2), and carbon monoxide (CO). Biogas production is commonly produced using an AD method (Galván-Arzola *et al.*, 2021) by utilising food and garden wastes, landfill, sewage sludge, animal manure (Mong *et al.*, 2020; Zhang *et al.*, 2018), agricultural wastes (Pan *et al.*, 2021a; Riya *et al.*, 2020; Weide *et al.*, 2020), and municipal solid wastes (MSW) (Lopes *et al.*, 2021; Pera *et al.*, 2021; Riya *et al.*, 2020; Zulkifli *et al.*, 2019) as a viable feedstock. LCB may be converted into biogas, which can then be utilised as a RE source for various purposes, including heat and power production. Additionally, digestate, a by-product of biogas generation, may be utilised as a fertiliser since it is nutrient-rich (Fatma *et al.*, 2018).

Utilising organic plant materials from plant sources, such as agricultural leftovers, wood waste, and energy crops, is necessary for manufacturing biogas from LCB (Fatma *et al.*, 2018). Moreover, complex carbohydrates within the biomass, such as cellulose and hemicellulose, can be biochemically processed into biogas. Pre-treatment of the biomass materials is the initial stage in generating biogas from LCB to increase its accessibility to microbial breakdown and decrease recalcitrance. One may utilise physical, chemical, or biological techniques to disassemble the intricate structures and liberate the carbohydrates. Following pre-treatment, the biomass is put through an enzymatic hydrolysis process, in which enzymes convert the cellulose and hemicellulose into simple sugars. According to Baruah *et al.* (2018), these sugars act as substrates for microbial fermentation. Microorganisms, especially methanogenic bacteria, ferment the carbohydrates in an anaerobic digester to produce biogas. Most of the biogas produced from LCB comprised CH_4 and CO_2. Those gas ratios are influenced by a number of variables, such as feedstock and anaerobic digester operating parameters. The substrates undergo complex biochemical processes comprising four stages: Hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Zulkifli *et al.*, 2019) (*Figure 4*).

Generally, the hydrolysis stage is much faster than the rest of the digestion phase in most AD processes (Vivekanand *et al.*, 2014). This is attributed to the fact that amorphous cellulose is easily digested during the step, depending on the pore size of the substrate. At the same time, crystalline cellulose is much harder for microbes to degrade during hydrolysis (Kucharska *et al.*, 2018). This phenomenon is due to the surface area and the compact structure of cellulose that affects the efficiency of hydrolysis. Cellulose is regarded as an essential component of plant cell walls, where its polymerisation degree and crystallinity can pose a detrimental effect on enzymatic hydrolysis (McNamara *et al.*, 2015). The crystallinity of cellulose is described in the percentage of the crystal-like structures which ranged from 30%-80%. The crystallisation zone consists of better chain orientation, compact organisation, high density, solid intermolecular bonding and *vice versa* for the amorphous (non-crystalline) area. The order of hydrolysed cellulose started with amorphous domains, followed by the crystalline domains, as reported by Ling *et al.* (2016), where the yield of monosaccharides dropped as the crystallinity of the substrate increased. Moreover, each cellulase component has its specific capabilities and activity for the adsorption of different types of cellulose through carbohydrate-binding modules (CBMs) during the breakdown of cellulose (Chaudhari *et al.*, 2023).

Furthermore, some digestion process-based factors could also contribute to the decline in biodegradation of lignocellulose biomass. For instance, the bioconversion process can generate additional inhibitors in the substrate during AD, such as NH_3, sulphide or sulphur, light metals, heavy metals, oxygen and organic compounds (Czatzkowska *et al.*, 2020), in addition to the harmful variation of the cell wall structure. The presence of inhibitors in the fermentation medium could undermine the microbial processes (Liu *et al.*, 2021). In addition, severe reduction of the substrates' pore size can trigger excessive generation of Volatile Fatty Acids (VFAs) as inhibitors and can delicately transform their chemical constituents (Magdalena *et al.*, 2019). Moreover, substrate delignification



Source: Zulkifli *et al.* (2019).

Figure 4. Mechanisms involved in biochemical degradation of substrates.

above 50% can cause the cellulose matrix to collapse, resulting in a compact and disordered structure and a subsequent reduction in cellulose availability (Ding *et al.*, 2018). Finally, bacterial decomposition processes of the organic matter/substrate without the presence of oxygen, yield the CH_4-rich biogas (Lim *et al.*, 2017).

DEVELOPMENT AND IMPLEMENTATION OF BIOGAS PLANTS IN MALAYSIA

In 2018, the World Biogas Association reported that Malaysia had installed 68 MW of biogas capacity, with an additional approved 73 MW, yielding 226 GWh of RE, which could avert the generation of almost 464 ktons of CO_2 emissions (US Energy Information Administration, 2020). Meanwhile, in the following year, biogas retained a total installed capacity of 148 MW 2019 (Energy Commission, 2021), which came from landfill and agricultural waste, with an estimation to reach up to 360-400 MW by 2020 and a projected energy reserve of 410 MW by 2030. A review of the resource potential for Malaysia RE was conducted by SEDA Malaysia (SEDA, 2021a), with the biogas potential identified to reach 736 MW, among other sources of bioenergy: Biomass (2.3 GW) and municipal solid waste (516 MW).

Lagoon systems and continuously stirred tank reactors are the two most frequently used technologies for producing biogas in Malaysia (Chan & Chong, 2019). However, in recent years, Malaysia's industry has started shifting attention towards high-level anaerobic bioreactors, comprising of advanced Anaerobic Expanded Granular Sludge Bed (AnaEG) and Integrated Anaerobic-Aerobic Bioreactor (IAAB) (Chan *et al.*, 2020; Lim *et al.*, 2021). The shifting is due to the bioreactors equipped with a biogas capture system, exhibiting better treatment efficiency, and producing lower carbon footprint (Chan & Chong, 2019). Usually, biogas production has lower purity of targeted gas, and the typical composition of biogas produced for CH_4, CO_2, N_2, O_2, CO, H_2S and NH_3 are 55.00%-77.00%, 19.00%-45.00%, <8.10%, 0.00%-2.10%, 0.00%-0.01%, 1-8,000 ppm and 0-7 ppm respectively (Korbag *et al.*, 2020). In order to obtain biogas with superior properties, the biogas produced must be cleaned and upgraded to improve the quality of biogas, to make it more suitable for power generation, gaseous car fuel and as a feedstock for the manufacturing of value-added chemicals (Zain & Mohamed, 2018).

Felda Sg. Tengi Palm Oil Mill in Selangor, Malaysia, a 400 m^3/hr biogas upgrading plant, was built in 2015 by Felda Palm Industries Sdn. Bhd. (FPISB), Sime Darby Offshore Engineering

Sdn. Bhd. (SDOE), and MPOB. The upgrading of the generated biogas using membrane technology produced CH_4 content of over 92%, CO_2 levels of 7%, and H_2S levels of 5 ppm (Lim *et al.*, 2021). The biogas upgrading also includes the following technologies- Pressure Swing Adsorption (PSA), water scrubbing, amine scrubbing, organic physical scrubbing, and membrane separation (Lim & Goh, 2019). Despite the adoption of industrial-scale AD in Malaysia, the application is still in its incipient stage compared to other developed countries. Against this background, several industries have begun to explore biogas production from agro wastes. *Table 1* summarises the significant activities of using AD to produce CH_4 from various agro wastes in Malaysia. It can be observed that POME has the highest energy potential compared to animal waste, with 40.19 GWh/yr, confirming its potential to convert waste into wealth (Kumaran *et al.*, 2015). *Table 1* also showcases different biogas plants utilising POME with an in-ground bioreactor system, generating electricity primarily for on-site use or to feed into the national power grid managed by Tenaga Nasional Berhad (TNB). *Table 1* also displays information about three different biogas plants - Cenergi Sri Ganda, FGV's Triang Palm Oil Mill, and GLT BP Power Sdn. Bhd., - highlighting their capacities and respective years of operation.

The biogas produced from POME is mainly used to generate energy for gas-powered appliances and on-site consumption. It was indicated that the collection of CH_4 via AD is expected to produce 16.91 TWh, resulting in a reduction of 11.35 million tonnes of CO_2 equivalent (Kumaran *et al.*, 2015). This also suggests that AD systems can provide 12.03% of the estimated power consumption in 2020, around 140.61 TWh, thereby lessening reliance on depletable fossil fuels. Given its significance, using POME as a biomass source has the potential to reduce environmental impact significantly (Jamali *et al.*, 2021). Apart from POME, the industries have also utilised animal wastes from cattle and chicken to produce biomethane. According to Abdeshahian *et al.* (2016), cows are the primary source of manure in Malaysia, generating approximately 5.45 t of waste annually. Due to the potential for odour issues and the emission of GHG, it is crucial to manage this manure production appropriately (Aili Hamzah *et al.*, 2020).

Almost 308.3 million chickens in the livestock subsector have been recorded by the DOSM, generating huge waste annually (Mahidin, 2019). This excessive quantity of animal waste can negatively affect the environment due to its high content of nutrients, which are N_2 and phosphorous (Gopinathan *et al.*, 2019), as well as harmful substances such as growth hormones, antibiotics, and heavy metals (Abdeshahian *et al.*, 2016). Excessive accumulation of these nutrients can lead to eutrophication phenomena that may affect water resources, including the aquatic environment. Besides that, dairy manure generation has also increased tremendously due to the increased number of cattle on the farms. In 2020, around 700,000 cattle were recorded across Peninsular Malaysia (FAOSTAT, 2023). Hence, it was estimated that in 2020, about 28,150 m^3 of CH_4 could be generated from cattle manure, resulting in the CH_4 production of 1,670,268 kWh/day (Gopinathan *et al.*, 2018).

There are 457 operated palm oil mills in Malaysia (MPOB, 2020; SEDA, 2021a), producing approximately 50-75 million m^3 of POME every

TABLE 1. LARGE-SCALE AGROWASTE METHANE PRODUCTION IN MALAYSIA

Agro-waste	Industries	Technology	Usage	Installed methane capacity	References
Cattle manure	Malaysian Veterinary Services	Fixed dome digester	On-site electricity and gas power	0.19 GWh/yr	Kumaran *et al.* (2015)
Chicken manure	QL Poultry Farm Sdn. Bhd.	Multi-stage anaerobic digester tank	On-site electricity	4.21 GWh/yr	Lim *et al.* (2021)
POME	FELDA Besout, Perak	Closed anaerobic pond	On-site electricity	40.19 GWh/yr	
POME	Cenergi Sri Ganda	In-ground bioreactor system	On-site electricity TNB's power grid	2.4 MW	Cenergi SEA Berhad (2023)
POME	FGV's Triang Palm Oil Mill	In-ground bioreactor system	On-site electricity (0.4 MW) TNB's power grid (2 MW)	2.4 MW	FGV Holding Berhad (2020)
POME	GLT BP Power Sdn. Bhd.	In-ground bioreactor system	TNB's power grid	3.6 MW	Green Lagoon Technology Sdn. Bhd. (2023)

year (Foong *et al*., 2021) with 95.5 million tonnes of fresh fruit bunches (FFB) annually (SEDA, 2021a). POME is generated from processing palm oil, which requires abundant water usage, and almost half of the waste produced ends up as liquid waste (Aziz & Hanafiah, 2017). The total annual production of POME has become a serious problem towards the ecosystem and public safety. In addition, POME can be linked to the high amount of biological oxygen demand (BOD) and chemical oxygen demand (COD) due to the elevated amount of organic content. Under the National RE policy, along with the glut production of POME and other agricultural wastes. With the rising interest in the biogas sector, the urgency to utilise these wastes as substrates for biogas production has received significant attention from the Malaysian government. From 2012-2017, more than 20 POME biogas plants and three landfill-based biogas plants were successfully constructed and commissioned (Gopinathan *et al*., 2018). The biogas plant's power output has gradually increased from 7,465-136,004 megawatt-hour (MWh). In 2020, within the FiT program, approvals were granted for 224 MW of biogas and 165 MW of biomass power plants (SEDA, 2021a). Notably, the predominant rise in capacity was observed in biogas plants. The statistics for biogas plants and power generation are expected to keep rising in the subsequent years since Malaysia is the second-largest producer of palm oil in Southeast Asia after Indonesia. The country recorded approximately 34.3% of global palm oil exports in 2020 [Malaysian Palm Oil Council (MPOC), 2021].

BIOGAS PRODUCTION FROM LIGNOCELLULOSIC BIOMASS

The primary feedstock for biogas production comes from lignocellulosic substrates derived from agricultural leftovers. This method is one of the key sources of sustainable bioenergy and aids in effective waste management. Despite their promise as a feedstock for biogas production, these materials exhibit biomass recalcitrance, defined as high resistance to biological breakdown due to their complex composition and structural organisation. The lignin-carbohydrate complex, also known as the lignin-hemicellulose complex, is a matrix of interlaced hemicellulose and lignin that contains cellulose microfibrils. It also provides a barrier to effective biological degradation (Mirmohamadsadeghi *et al*., 2020; Zoghlami & Paës, 2019). Therefore, methods to lessen biomass resistance are required to increase the availability of lignocellulosic materials for anaerobic microbial breakdown.

Pre-treatment is an essential component of the cellulose transformation process, and it is critical to alter the structure of the cellulosic biomass so that the enzymes which convert carbohydrate polymers into fermentable sugars may better utilise the cellulose (Ma *et al*., 2022). The various feedstock structures are altered at all fibre levels during pre-treatment. The pre-treatment of using biological, physical, chemical, and thermal agents, modifies the amount, proportion, and morphological properties of the lignocellulosic materials. However, none of these technologies has yet been proven to be efficient or cost-effective. Additionally, the ideal pre-treatment factors are not often specified. These findings are crucial for the efficient and useful utilisation of the diverse leftovers produced by agricultural activities.

Biohydrogen and Biomethane Production from Lignocellulosic Biomass

The recalcitrant character of LCB exhibits a technological problem for producing fermentable sugars from biomass and reduces the potential of its utilisation in biorefinery (Bhatia *et al*., 2020). The physicochemical properties of the biomass cells are significant factors contributing to the recalcitrant nature of LCB (Zoghlami & Paës, 2019). Furthermore, LCB has high stability and is highly recalcitrant, with standing enzymatic and bacterial attacks. Its intricate structure limits microbial degradation, thus slowing the substrate degradation during the hydrolysis stage. As indicated in *Figure 5*, biopolymers cellulose (11%-46%), hemicellulose (6%-42%) and lignin (1%-40%) are the three primary biopolymers discovered in lignocellulosic materials (Soares *et al*., 2019). Hemicellulose acts as a matrix surrounding the cellulose skeleton. In contrast, lignin acts as an encrusting substance that protects the cellulose skeleton (Amin *et al*., 2017), creating resistance towards effective biological breakdown. Based on studies from Thomsen *et al*. (2013), a 1% increase in lignin concentration results in an average decrease of 7.49 L CH_4/kg TS. This was further corroborated by Triolo *et al*. (2012), who stated that an excess of lignin of more than 100 g/kg VScan significantly reduces CH_4 output.

The relationship between lignin content and biomass degradation is further elucidated by two mechanisms. Firstly, lignin strengthens the cell wall structure by forming covalent bonds with other cell wall components, thereby increasing space resistance. This prevents carbohydrate breakdown by enzymes, and the second mechanism is the binding ability to enzymes (Lu *et al*., 2016). Lignin can alter enzymatic hydrolysis by adsorbing cellulase in a non-specific or non-productive manner. The accessible surface area also plays a vital role in the digestion and biodegradability of lignocellulosic materials, requiring the substrate to have sufficient pore sites available for optimal hydrolysis (Karimi & Taherzadeh, 2015).

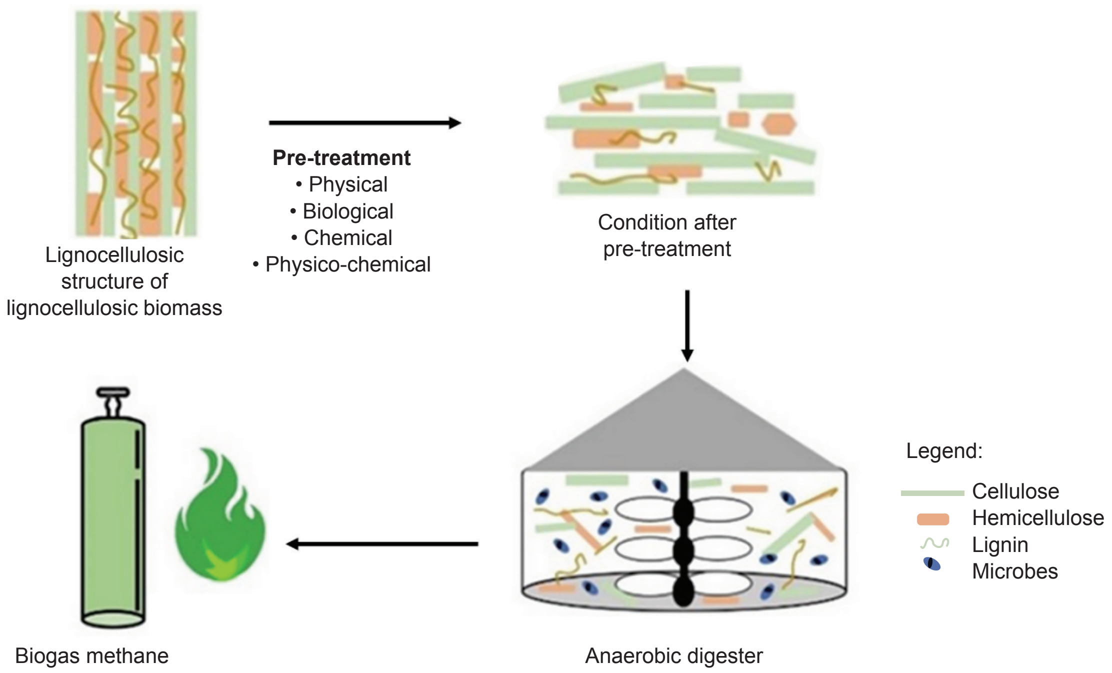


Figure 5. Schematic representation of pre-treatment of lignocellulose biomass during the AD process.

Several LCBs have been explored to produce biogas and bio-hydrogen, as reported in previous studies (Bhatia *et al.*, 2019; Yatim *et al.*, 2017). These LCBs include rice husk, oat straw, corn stover, sugarcane bagasse, EFB, poplar leaves, rice husk, wheat straw, empty palm fruit bunch, pine tree wood and others. These LCBs have generated substantial biogas and bio-hydrogen due to their inherent unique properties, nature or type of inoculum used and operating conditions. *Table 2* summarises the research findings on LCB utilisation for bio-hydrogen and biogas production. Based on these findings, LCB has demonstrated an outstanding performance in producing bio-hydrogen and biogas. Since LCB has abundant sources and feedstock, the utilisation and exploitation of LCB could play a significant role in advancing sustainable energy in Malaysia.

Pre-treatment Techniques of Lignocellulosic Biomass

The degradability of lignocellulose feedstock is affected by many variables, including lignin content, crystallinity, polymerisation grade, surface area, and solubility. Different researchers have applied different pre-treatment procedures to improve lignocellulosic feedstock bio-digestion and CH_4 release. Pre-treatment techniques are selected based on the physicochemical properties and structural makeup of the feedstock. It is anticipated that they will enhance the creation of organic feedstock while keeping the matter in the process. Thus, pre-treatment is essentially required to accelerate the hydrolysis process and break up the lignocellulose structure (Aftab *et al.*, 2019). Techniques for biological, chemical and physical pre-treatment include extrusion, steam explosion, liquid hot water, enzyme, fungi, acid, alkali, ionic liquids, organo-solvents, ozonolysis and size reduction (Olatunji *et al.*, 2021; Zhu & Pan, 2022). Pre-treatment of the substrate prior to both AD and ethanol production is performed for the same reasons. However, the only difference is that since microorganisms are involved in AD, crystalline compounds (cellulose and hemicelluloses) can be broken down with less cost for the pre-treatment process (Olatunji *et al.*, 2021).

The two primary aims of pre-treatment before AD are the dissolution of the bio-polymeric linkages and the opening of the materials. In general, pre-treatments aim to ensure easier interaction between the enzymes with the cellulose and hemicelluloses. This causes the feedstock to economically degrade, avoids degradation loss, thus preventing the release of potential inhibitors, as well as reduces the possible impact on the environment (Den *et al.*, 2018). Therefore, it is critical to have a detailed review of the biological, chemical, and physical pre-treatment techniques. Against this background, numerous preliminary treatment strategies have been identified and explored to advance the efficiency of the hydrolysis process during AD to enhance biogas production. *Table 3* compiles a thorough summary of research outcomes regarding biogas production from widely accessible LCB in Malaysia. It encompasses diverse pre-treatment methods feasible for implementation within the country. Additionally,

TABLE 2. SUMMARY OF FINDINGS ON LIGNOCELLULOSIC BIOMASS UTILISATION FOR BIOGAS PRODUCTION

Type of lignocellulosic biomass	Method	Inoculum used	Operating conditions	Biogas production	Challenges	References
Corn stover	Photo fermentation (PF), Dark fermentation (DF) and Dark-photo co-fermentation (DPCF)	DF: *Enterobacter aerogenes* PF: Photosynthetic bacteria *HAU-M1*	Working volume: 200 mL PF: pH: 6.5, light intensity of 3,500 Lux, Temp: 30°C DF: pH: 6.5, Temp: 35°C and without light DPCF: pH: 6.5, light intensity of 3,500 Lux, Temp: 30°C	Maximum cumulative H_2 HHH yield: 141.42 mL/g TS achieved by PF	High accumulation of volatile fatty acids during DF hampered the production of H_2	Riya *et al.* (2020)
Oat straw	Anaerobic digestion	Anaerobic granular sludge	Working volume: 80 mL, pH: 7.0, speed: 150 rpm and Temp: 35°C	H_2 yield: 94.4 mL H_2/g oat straw	Inhibitors (furfural, HMF, vanillin and syringaldehyde) causes low H_2 yield	Arreola-Vargas *et al.* (2015)
Empty palm fruit bunch (EFB), rice husk (RH), and pine tree wood (PTW)	Anaerobic dark fermentation	Heat-treated anaerobic digester sludge	Working volume: 40 mL pH: 7.0-7.5, speed: 150 rpm and Temp: 35°C	H_2 production yield: EFB = 2,640 mL/L/day RH = 2,960 mL/L/day PTW = 2,565 mL/L/day	Generation of inhibitors such as 5-HMF and furfural hinder the H_2 production rate	Gonzales *et al.* (2016)
Rice straw	Anaerobic digestion	Pond sediments sludge	Working volume: 2.2 L Incubation Temp: 35°C pH: 7.3	Biogas: 393.2 ± 13.6 mL/g VS CH_4: 224.4 ± 6.8 mL/g VS	Inconsistent performance of substrate digestion for co-substrate or fed-batch system	Pan *et al.* (2021b)
Rice straw and cow dung	Anaerobic co-digestion with cow dung	No inoculum used	Working volume: 30 L Dung-to-straw ratio: 3:1 (based on TS) 8 C/N ratio: 20:30	Biogas: 434.2 L/kg VSr CH_4: 217.6 L/kg CH_4 yield: 217.6 L/kgVSr	Rice straw has a high C/N ratio or low hydrolysis performance and digestibility	Haryanto *et al.* (2018)
Rice straw	Anaerobic digestion	Anaerobic wastewater sludge	Working volume: 500 mL Incubation Temp: 35°C, pH: 7	Biogas: 322.1 mL/g rice straw	No acknowledgement of this substrate for biogas production in Thailand	Amnuaycheewa *et al.* (2016)
Corn stover	Anaerobic digestion	Mesophilic biogas plant of pig manure sludge	Working volume: 8 L Organic loading rate: 90 g $TS \cdot L^{-1}$, retention period: 60 days, pH: 7.2, Temp: 35°C, 38°C, 41°C and 44°C	Biogas: 598 mL/g VS/d CH_4: 308 mL/g VS/d	High incubation temperature for optimum biogas production leads to high energy usage	Liu *et al.* (2017)
Empty fruit bunch (EFB)	Anaerobic co-digestion with POME	Anaerobic sludge from palm oil mill	Different EFB to POME ratios EFB sizes: 0.5-6.0 cm Total solid of substrate: 2-10 g VS at 37°C	CH_4: 323 mL/g VS	Size reduction of EFB up to 0.5 cm requires high energy and is expensive	Saelor *et al.* (2017)
Poplar leaves	Anaerobic fermentation	No inoculum used	pH: (6.0-8.0), TS: (8%-12%) and Temp: (25°C-35°C)	Biogas: 39,625 mL	The substrate needs to be pre-treated with alkali to achieve optimum biogas production	Zhang *et al.* (2020)
Wheat straw, rice straw and sugarcane bagasse	Anaerobic co-digestion	Effluent of the operational biodigester of cow manure	Substrate to inoculum (S/I) ratio: 1.5:2.5 Working volume: 210 mL pH: 7.0-7.5, Temp: 35°C	Best S/I ratio: 1.5 CH_4: 393.08 $NmLCH_4$/g VS	Low hydrolysis rate, high lignin content and low pH value (accumulation of volatile fatty acids)	Meraj *et al.* (2021)

TABLE 3. INFLUENCE OF PRE-TREATMENT TECHNIQUES ON THE PRODUCTION OF BIOGAS

Type of lignocellulosic biomass	Method of biogas production	Pre-treatment methods		Treatment condition	Treatment mechanism	Major findings	References
		Type	Pre-treatment				
Rice straw	Anaerobic digestion	Chemical	Sodium carbonate, Na_2CO_3	0.25 and 0.5 M Na_2CO_3 at 90, 110, and 130°C for 1, 2, and 3 hr	Significantly reduce the crystallinity of cellulose and lignin content	0.5 M Na_2CO_3 at 110°C for 2 hr = 292 mL CH_4/g VS	Dehghani *et al.* (2015)
	Solid-state anaerobic digestion	Physical	Milling	Milled to the particle diameter of ≤2 mm	Can increase lignin and hemicellulose, and cellulose removal	Milling posterior to fungal pre-treatment results in the highest effect	Mustafa *et al.* (2016)
		Biological	*Pleurotus ostreatus* fungus	70% moisture content at 28°C for 10, 20 and 30 days	Degrade dry matter, cellulose, hemicellulose and lignin in rice straw		
	Anaerobic digestion	Chemical	Organic acid - acetic acid, $C_2H_4O_2$ - citric acid, $C_6H_8O_7$ - oxalic acid, $C_2H_2O_4$ Inorganic acid -Hydrochloric acid, HCl	Org. acid concentration (5%-15% wt), inorg. acid concentration (0.5-2.0 wt), treatment time (30-60 min), and reaction temperature (100°C-140°C)	Can reduce the large amount of rice straw mass into reducing sugar and lignin content to remove inhibitors of a hydrolysis reaction	$C_6H_8O_7$ pre-treated substrate is the best method Biogas yield: 197.86 mL/g VS_{total} COD removal: 73.2%	Amnuaycheewa *et al.* (2016)
Paddy straw	Anaerobic digestion	Physico-chemical	Sodium hydroxide microwave	Substrate soaked in sodium hydroxide (NaOH) solution at 2%-10% concentrations for 24 hr at 28°C. Then, irradiated with microwaves at 720 W, 180°C for 30 min	Co-pre-treatment reduced lignin and silica content while breaking lignocellulose structure by tearing different layers of the cell wall of paddy straw	Best pre-treatment at 4% NaOH-30 min microwave Biogas yield: 297 L biogas/kg substrate	Kaur & Phutela (2016)
Corn stover	Anaerobic digestion	Physico-chemical	Steam explosion	Steam explosion unit: 25 KW electric-heated steam boiler with pressure of 34 bar (maximum) Pre-treatment temperature ranges from 140°C to 220°C for 2 to 15 min	Acetyl groups in the hemicellulose fraction will be hydrolysed, producing a lot of acetic and uronic acids that reduce the pH value in the substrate sample	The best pre-treatment was conducted at 160°C for 2 min Biogas yield: 585 L/kg VS CH_4: 348 L/kg VS	Lizasoain *et al.* (2017)
Corn stalk	Anaerobic digestion	Physical	Dual-frequency ultrasound	Mass of corn stalk (40-64 g), ultrasonic duration time (10-50 mins), alkali pre-treatment (2% NaOH) time (0-72 hr), and single/dual-frequency ultrasound	Mechanisms of ultrasonic is the cavitation effect, where its intensity is related to the ultrasonic frequency and the ultrasonic intensity	Cum. Biogas yield: 0.501 L/g VS with higher 56.6% than other pre-treatment methods	Dong *et al.* (2018)

TABLE 3. INFLUENCE OF PRE-TREATMENT TECHNIQUES ON THE PRODUCTION OF BIOGAS (continued)

Type of lignocellulosic biomass	Method of biogas production	Pre-treatment methods		Treatment condition	Treatment mechanism	Major findings	References
		Type	Pre-treatment				
Sugarcane bagasse	Anaerobic digestion	Chemical	Ethanolic ammonia	10% v/v aqueous ammonia solution at 50 and 70°C for 12 and 24 hr Concentrations of ethanol added to the pre-treatment mixture: 5%-50% v/v	Pre-treatment increases lignin removal and reduces cellulose crystallinity to improve CH_4 yields	At 70°C, Highest CH_4 yield: Liquid fraction, 298.0 mL/g VS whole slurry, 299.3 mL/g VS solid fraction, 248.6 mL/g VS	Hashemi *et al.* (2019)
Empty fruit bunch (EFB)	Solid-state anaerobic digestion	Chemical	NaOH solutions	3%-7% w/v of NaOH	Those pre-treatments increase the surface area, cellulose content, and the concentration of reduced sugar	Size reduction gave the highest yield of CH_4: 429.9 mL/g VS, more than a 90% increase compared to raw substrate	Wadchasit *et al.* (2020)
		Physical	Size reduction	3.0 and 0.5 cm			
		Biological	Activated sludge (AS) and bio-scrubber effluent	10 g of substrate pre-treated with AS and effluent separately			

the overview focuses on several kinds of LCB often discovered and conveniently available in Malaysia, especially those produced by agricultural pursuits such as paddy cultivation, maize farming, sugarcane production, and palm oil plantations. Generally, most pre-treatment techniques can expand the surface area and produce readily available active binding sites for enzymes to thrive (Karthikeyan *et al.*, 2018). The benefits of various pre-treatments include increased surface area, lignin removal, and decreased cellulose crystallinity (Paudel *et al.*, 2017).

Physical Pre-treatment Method

In the physical pre-treatment technique, milling or grinding the LCB is conducted to break down the particle sizes (Arenas-Cárdenas *et al.*, 2017). The outputs of physical treatments could be influenced by the operating temperature, pressure, feedstock, and residence time. Mechanical pre-treatments are inadequate for the pre-treatment of LCB and are usually merged with chemical pre-treatments to enhance downstream carbohydrate products (Kumar & Sharma, 2017). The physical processes are undertaken at temperatures ranging between 180°C and 240°C, together with mechanical shearing. However, physical or mechanical pre-treatment methods such as mechanical comminution, microwave radiation, freezing method with a volumetric water change, extrusion, and sonication or ultrasound-assisted pre-treatment, do not use chemicals or microbes (Xu *et al.*, 2019).

Agricultural waste and forestry residues are commonly subjected to mechanical processing to improve the lignocellulosic material's accessibility to hydrolysable polymers (Amin *et al.*, 2017). These methods can improve the efficiency of hydrolysis and anaerobic breakdown of plant biomass into liquid and gaseous fuels and other essential organic compounds. Numerous physical pre-treatment approaches are employed to enhance biogas production. These physical techniques include grinding, ultrasound, milling, microwave, irradiation, external forces assisted and size reduction (Dong *et al.*, 2018; Mustafa *et al.*, 2016; Wadchasit *et al.*, 2020; Xu *et al.*, 2019). However, the utilisation of this pre-treatment approach requires prolonged retention times and high energy requirements (Baruah *et al.*, 2018).

Chemical Pre-treatment Method

For the chemical pre-treatment method, chemical reactions in aqueous solutions enable lignocellulose degradation to simple molecules (Kucharska *et al.*, 2018). These methods can be classified into acid hydrolysis, alkaline pre-treatment, ozonolysis, solvents (organic and others) and ionic liquid pre-treatment. However, this pre-treatment is more common than physical and biological pre-treatment procedures due to its efficacy and ability to increase the digestion of complicated feedstocks. Despite this efficacy, the formation of inhibitory compounds such as phenolic acids, furfurals, aldehydes and 5-hydroxymethylfurfural has restricted the more comprehensive application of this technique (Olatunji *et al.*, 2021). This technique also improves bioconversion performance due to its enhanced effectiveness in reducing resistive characteristics (Xu *et al.*, 2019). Chemicals often utilised in chemical pre-treatment procedures for enhancing agricultural residue AD performance include hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), acetic acid (CH_3COOH), lime [$Ca(OH)_2$], and potassium hydroxide (KOH) (González *et al.*, 2005; Olatunji *et al.*, 2021).

Acid pre-treatment can hydrolyse hemicellulose to monosaccharides, increasing the cell wall's pore size or volume and making cellulose more vulnerable to enzymatic breakdown. The addition of bases to biomass causes swelling, which increases internal surface, decreases polymerisation degree and crystallinity, disrupts connections between lignin and other polymers, and lignin breakdown (Badiei *et al.*, 2014), making it more effective for biomass with low lignin concentration. Chemical pre-treatment for biomethane production from LCB and acidic pre-treatment produces the highest biomethane production. This indicates that it could be considered as a good pre-treatment media, despite the substantial production of biomethane from LCB using chemical pre-treatment. Yet the application of this approach could generate high corrosivity and toxicity, environmental pollution, prolonged residence time, formation of inhibitors and toxic and high energy requirements (Amnuaycheewa *et al.*, 2016; Dehghani *et al.*, 2015; Hashemi *et al.*, 2019).

Physicochemical Pre-treatment Method

The physicochemical method combines oxidation and heat treatment to decompose lignocellulose structure. This method comprises steam explosion (autohydrolysis), Ammonia Fiber Explosion (AFEX) (Cai *et al.*, 2022), and CO_2 explosion (Mussatto *et al.*, 2021). Steam explosion is run by subjecting lignocellulosic material to high-pressure saturated steam at a temperature of 160°C-260°C and a pressure of 5-50 atm for several minutes (Amin *et al.*, 2017). The AFEX pre-treatment, also called NH_3, to recycle percolation or called Ammonia Recycle Percolation (ARP) or Soaking Aqueous Ammonia (SAA), utilises liquid NH_3 to pre-treat lignocellulose. This pre-treatment is conducted at room temperature, whereas the ARP approach is at high temperatures. For CO_2 explosion, feedstock is contained in a high-pressure vessel where supercritical CO_2 is released and acts as a solvent. It combines both chemical and physical techniques as a single pre-treatment method. However, the more comprehensive application of this technique is restricted by the formation of pseudo-lignin, which may hinder CH_4 yield (Sun *et al.*, 2021). However, some drawbacks of this technique include environmental pollution, high temperature, and high energy requirements (Sharma *et al.*, 2023).

Biological Pre-treatment Method

Biological pre-treatments are predominantly environmental-friendly and non-hazardous, with lesser energy consumption, without generating inhibitors for downstream conditions, and relying on microbes, enzymes, or consortia to promote lignocellulose biodegradation and biogas production (Tu & Hallett, 2019). The biologically discovered broad systematic array of microbes is utilised in biological pre-treatment. They degrade or change lignocellulose extracellularly by producing hydrolytic enzymes such as hydrolases and ligninolytic enzymes, which depolymerise lignin. Furthermore, fungal or bacterial pre-treatments can be employed to depolymerise, hydrolyse cellulose and eliminate lignin (Chen *et al.*, 2017). The working conditions for biological pre-treatments are affected by chemical (such as pH), biological (a strain of fungi or bacteria), and physical (for instance, the size of the particles and temperature) circumstances (Sharma *et al.*, 2017). Moreover, the generation of bioethanol from biogas carbohydrate fermentation can also be generated based on the nature of the bacteria/fungi and retreatment applied.

However, applying the biological pre-treatment approach requires prolonged retention times. It is not commercially feasible since it generally requires other pre-treatment techniques, such as chemical or biological, to function efficiently. Some emerging pre-treatment techniques, namely supercritical fluid-based, ionic liquids, Low Temperature Steep Delignification (LTSD) and Co-solvent Enhanced Lignocellulosic Fractionation (CELF), are regarded to be the most advanced approaches that produce superior sugar yield with a minimal quantity of by-products (Meng *et al.*, 2018; Sorn *et al.*, 2019). Accordingly, the released hexose and pentose sugars can be applied to produce polyols, organic acids, fatty acids, bioplastics and alcohols by various microbes (Jagtap *et al.*, 2019).

CURRENT CHALLENGES AND DRAWBACKS OF BIOGAS PRODUCTION FROM LIGNOCELLULOSIC BIOMASS IN MALAYSIA

Recently, the Malaysian government launched the Malaysia Energy Supply Industry 2.0 (MESI 2.0) plan in 2019, with a new target of 35% RE in installed power capacity by 2025. Malaysia has reiterated its commitment to increasing the percentage of carbon-neutral energy sources as part of its efforts to tackle global climate change. Notably, the country has revised its target for RE in the national energy mix, raising it from 20%-31% by the year 2025 (Rahman *et al.*, 2022). Despite the vast growth of biogas plant utilisation to generate energy in Malaysia, there are several shortcomings which have hindered its development. These limitations include financial obstacles, market barriers, lack of indigenous technology, and poor access to grid connections for biogas power plants (Kumaran *et al.*, 2015). The principal financial hurdle is the investment cost of building biogas plant infrastructure with power production facilities. At the same time, the market barriers relating to the electricity market structure can be visibly observed to be very expensive compared to the current waste treatment practice.

Key challenges encountered by bioenergy developers, as listed by SEDA Malaysia, encompass various aspects: Firstly, issues of suboptimal plant size and capacity factors stem from challenges in acquiring feedstock. This is followed by concerns over fluctuating feedstock price and quality, complexities in accessing grid connections, and the utilisation of less efficient technologies for power generation. Furthermore, WTE players face their distinct issues, such as varying tipping fees across Malaysia, complicating investment decisions and logistical challenges in managing waste feedstocks due to scattered landfill sites across the country (SEDA, 2021a). The government also acknowledges the critical need to address both supply and demand challenges for agriculture-related bioenergy to meet its intended objectives. However, there are also supply-related hurdles, which involve potential concentration risks with bioenergy feedstock, global perceptions affecting the acceptance of palm oil biomass, biomass supply security and high aggregation costs of bio-based feedstock. On the other hand, demand challenges revolve around limited local demand for bioenergy (MoE, 2023).

Therefore, to curb the glut of agricultural waste generated in Malaysia, various agro-industries are currently considering strategies to reduce biomass waste generated by upgrading waste conversion or processing techniques. However, local funding institutions are still concerned about the sustainability of the biomass feedstock supply for an extended period. Malaysia's biogas sector is still in its early phases of growth (Amin *et al.*, 2022), and the main method of waste treatment is the use of anaerobic digesters, which employ microorganisms to break down waste. However, there is a dearth of biogas capture technology implementation, which could be secured by successful collaborations with government agencies (Hanafiah *et al.*, 2017). As of October 2023, Malaysia possessed a total of 447 palm oil mills with some of them equipped with biogas capture facilities as reported by the Malaysian Palm Oil Board (MPOB, 2023a). The majority of these biogas plants actively contributed to the national grid, showcasing a substantial commitment to sustainable energy practices within the country.

The utilisation of agricultural wastes as biogas substrates enhances waste management and serves as a critical renewable bioenergy source (Olatunji *et al.*, 2021). The application of agricultural wastes, especially lignocellulosic materials, has inherent limitations. Although LCB is rich in fermentable sugars, rendering them an ideal food source for microbes to produce biogas, their pre-treatment procedure still requires a huge sum of capital. In addition, their inherent drawbacks lie in their complicated compositional and structural arrangement that makes them recalcitrant to biological decomposition. Other challenges in utilising the lignocellulosic materials include their natural structure. Biomass recalcitrance and production of inhibitors are among the critical challenges limiting biogas and bioethanol production, leading to higher production costs and longer processing time (Xu *et al.*, 2019).

In addition, the biodegradability of LCB could be affected by the percentage or proportion of lignin, accessible surface area, cellulose polymerisation grade, crystallinity, cross-linkages of hemicellulose, solubility and other related factors (Xu *et al.*, 2019). Biomass degradation and modification to increase enzymatic digestibility are usually performed under severe conditions, requiring large amounts of chemicals, making the pre-treatment process more expensive (Capolupo & Faraco, 2016). In addition, the main challenge in biogas production from LCB, especially for small local industries, is the high cost of pre-treatment of the substrate to obtain higher biogas yield. The operating factors could also undermine the performance of various lignocellulose biomass (substrates) in biomethane production (Xu *et al.*, 2019).

ECONOMIC ANALYSIS OF PRE-TREATMENT METHODS FOR LIGNOCELLULOSIC BIOMASS IN BIOGAS PRODUCTION

In the quest for sustainable energy sources, LCB has emerged as a promising solution for biogas production. However, efficiently converting this abundant renewable resource into biogas poses significant challenges (Patel & Shah, 2021; Saini *et al.*, 2016). A critical aspect of this conversion process is the pre-treatment of LCB, which involves a series of physical, chemical, or biological processes, aimed at breaking down its complex structure and enhancing its accessibility for subsequent biogas production (Hernández *et al.*, 2019). The economic analysis of pre-treatment methods becomes crucial in evaluating their viability, optimising resource allocation and determining the overall financial feasibility of LCB-based biogas production systems.

Factors such as investment costs, operational expenses, biomass feedstock availability and costs and product revenues, significantly influence the potential economic profit of AD plants

(Bruno *et al.*, 2023). Moreover, the nascent nature of pre-treated LCBAD techniques introduces investment risks. This comprehensive analysis explores the economic factors and considerations associated with pre-treatment methods, providing valuable insights for policymakers, researchers and stakeholders invested in sustainable energy solutions. According to research, pre-treatment costs account for approximately 19%-22% of the total expenses in the bioenergy recovery process (Baral & Shah, 2017). Scientists have conducted techno-economic evaluations of the different pre-treatment methods to ensure energy efficiency and cost-effectiveness. The aim is to identify the optimal conditions that offer the best balance between cost and energy recovery in bioenergy production.

In the study by Dahunsi *et al.* (2019), acid pre-treatment of *Sorghum bicolor* stalk produces 312.3 LN biogas per kg of Volatile Solids (VS) added. However, there was a deficit in net thermal energy, which was -951 kWh/t of Total Solids (TS) and in net electrical energy, which was -753 kWh/t of TS. The capital investment for this project amounted to USD140 million. Note that the sulphuric acid pre-treatment used in the study on *S. bicolor* stalk demonstrated a high gas production. However, the negative net thermal and electrical energy values indicate a deficit in energy recovery. A thermo-alkaline method was employed for the pre-treatment of *Arachis hypogaea* (Peanut) hull. The pre-treatment resulted in gas production of 3,339.20 mL/kg of TS fed. The net thermal energy was -412 kWh/t of TS, while the net electrical energy was 303 kWh/t of TS. The capital investment for this project was USD450 million, with a Net Present Value (NPV) of USD381 million (Dahunsi *et al.*, 2017). The thermo-alkaline pre-treatment method applied to *A. hypogaea* hull demonstrated a favourable gas production, with a relatively balanced net thermal and electrical energy recovery. Accordingly, this pre-treatment indicates its potential for efficient bioenergy production.

Another study by Kabir *et al.* (2015) utilised organosolv pre-treatment on forest residue by comparing the performance of ethanol, CH_3COOH, and methanol on biogas production. The economic analysis indicates that using methanol for pre-treatment offers the highest NPV compared to alternatives utilising ethanol or CH_3COOH. This finding makes the methanol-based pre-treatment process the most economically attractive option. The primary factor contributing to its advantage is the low cost of methanol, priced at USD0.300/kg. Compared to the other alternatives, this cost advantage enhances the profitability and economic feasibility of the methanol-based pre-treatment method. Brand *et al.* (2013) investigated the economic analysis of mechanical pre-treatment for converting softwood biomass into fermentable sugars using three-phase milling. The cost of sugar production through this mechanical pre-treatment method was calculated to be USD0.496/kg. However, this study did not address the environmental and profitability aspects of the disintegration process. Furthermore, Safarian and Unnthorsson (2018) suggested that steam explosion pre-treatment is a highly efficient and profitable technique from an energetic, economic and ecological standpoint. Conversely, dilute acid pre-treatment is another effective method for LCB; however, it is less desirable due to higher production costs and increased GHG emissions. Soam *et al.* (2018) proposed treating LCB with alkali at lower doses prior to biological pre-treatment. This approach reduced the required enzyme dosage by 23%-39%. However, the authors also observed adverse ecological effects of this pre-treatment method.

Thus, further research is required to identify the optimal combination of disintegration methods and operational conditions that can effectively minimise ecological effects, reduce environmental impacts and decrease costs associated with pre-treatments. Notably, the expenses incurred for pre-treatment methods can be offset by producing excess bioenergy, resulting in a net gain. Nevertheless, when evaluating the profitability of the production process, it is crucial to consider both fixed capital investment and variable costs (Jamaldheen *et al.*, 2022). Additionally, it is recommended to assess the bioenergy productivity of all pre-treatment methods, when dealing with a fixed quantity of lignocellulosic feedstock. This comprehensive evaluation will provide a more accurate assessment of the process's profitability.

In evaluating pre-treatment methods, it is crucial to consider their environmental and economic impacts to ensure the sustainable production of bioenergy (Pérez-Almada *et al.*, 2023). Moreover, balancing economic gains with environmental sustainability through a comprehensive assessment of pre-treatment methods is vital for the long-term viability of biogas production from LCB (Preethi *et al.*, 2023). This balanced approach ensures economic profitability while mitigating adverse environmental effects.

FUTURE PROSPECTS

Though preliminary treatment is necessary to enhance bio-energy production, the constraining impact resulting from the lignin and hemicellulose degradation is unignorable. Therefore, it is a considerable concern to adequately balance functional bacteria actions and the lignocellulose derivative inhibitors production to optimise bioenergy generation from lignocellulose substrate. The commercial adoption of either pre-treatment technique is relatively rare due to the significant drawbacks of each operation. Thus, the industrial-friendly and economical approach to pre-treat LCB should be explored and developed. Hence, lowering the treatment period together with reduced wastage may be favourable to reducing the overall pre-treatment cost. In this regard, the thermal-related pre-treatment (such as microwave) process could offer a reduction in residence time compared with other existing pre-treatment technologies.

This review suggests a robust comparative study of various pre-treatment technologies with a single variety of LCB. The main challenge has been the disparity in the makeup of lignocellulosic feedstock biomass with the differences in location. Thus, choosing a good pre-treatment technique could avert unnecessary difficulties during biogas production. A low-cost, practical, environmentally friendly and facile operation pre-treatment system should be exploited to enhance the existing AD reactors. Also, an integrated, optimised AD system with pre-treatment compartments is another grey area that can assist in minimising the residence time and the overall duration of biogas production. This echoes the need for further in-depth study on the inline pre-treatment-AD integrated system. Further study on the development of inline pre-treatment-AD integrated system may involve investigating the biomass feeding rate, retention time and operating conditions such as temperature and pH. This includes the design that ensures optimal biogas production conditions in terms of yield volume, feedstock retention time and reactor compatibility.

In addition, identifying the pre-treatment methods capable of breaking up the complex feedstock into simpler molecules is crucial in achieving a novel and efficient biogas production system. This demonstrates that the success of this inline integrated pre-treatment-AD system will significantly change the paradigm of biogas production in Malaysia and beyond. However, the meagre implementation and inadequate adoption of this technology among the stakeholders could undermine the impact on the biogas industries. To avoid this, the relevant government agencies in Malaysia, such as NEEAP in conjunction with the EECA, may be charged with demonstrating and promoting the technology to get it across to the stakeholders (such as the farmers and biogas industries).

CONCLUSION

This article presents a review of biogas production from LCB in Malaysia. Initially, it deliberates on the energy sources, the potentials of the abundant biomass generated, the chemistry compositions of the biomass and its applications. This should assist the Malaysian government in initiating several policies to develop biogas plants with the aim of reducing dependence on fossil fuels. This improved the contribution of the biogas energy value to the national energy requirement compared to other energy sources. Furthermore, the various sources of LCB in Malaysia and the respective potential utilisations are deliberated. The yearly generation of lignocellulosic biomass (LCB) is substantial; however, its potential for biogas production remains largely untapped. Despite this underutilisation, the energy value derived from biogas is comparable to other sources like hydro and solar energy. The hydrolysis process during LCB degradation is notably prolonged due to the intricate nature of cellulose compounds, thereby impeding the initial biochemical reactions. To expedite biogas production, physical, chemical and biological pre-treatments are predominantly employed. The delay in biochemical degradation triggers hydrogen partial pressure, resulting in the formation of volatile fatty acids (VFAs) that inhibit the methanogenesis process. This underscores the imperative for further investigation into the development of an inline integrated pre-treatment-anaerobic digestion (AD) system, coupled with an exploration of optimal operating conditions. The prospect of efficient biogas development and production from LCB in Malaysia hinges on various factors, including governmental policies, inherent physicochemical attributes of the feedstocks and operational conditions. These economic analyses provide valuable insights for policymakers, researchers, and stakeholders engaged in sustainable energy solutions utilising LCB. Therefore, enabling policies and availability of an efficient inline integrated pre-treatment-AD system capable of utilising the ever-generating biomass will not only consolidate its national energy contribution but also improve environmental conditions.

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