

Recent Challenges of Biogas Production and its Conversion to Electrical Energy

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ABSTRACT

A pressing concern of issues such as climate change has drawn main attention in the world. The burning of fossil fuels by human due to increasing energy demand in various sectors is one of the main factors that influence the climate change. This has resulted in the introduction of many renewable energy sources as alternatives to fossil fuels. Biogas is one type of renewable energy that has numerous advantages. The present review covers the recent challenges of biogas production and its conversion to electrical energy. This includes the substrates used, the operating parameters, and the pre-treatment used, which can be implemented to maximise the biogas yield. The challenges and potential of the generation of electricity from biogas were also discussed in this review. The results obtained in this review emphasise that biogas is a good renewable energy, as it solves multiple problems and at the same brings benefits to human beings in many ways.

Keywords: biogas; methane gas; electrical energy; anaerobic digestion; energy.

INTRODUCTION

Energy has become an essential element in the development of various sectors in many countries all over the world, including Malaysia. The transportation sector has been the main energy consumer since the early 2000s. As the population has increased each year, energy consumption resulting from the construction of buildings and industrial activities has surpassed the transportation sector, in order to meet the demand of daily life. This has been to ensure that Malaysia can compete with other nations. It is estimated that 40% of energy is consumed by buildings, 32% is consumed by industrial activities, and the remainder is consumed in the

transportation sector (Ahmad et al., 2017). For buildings and industries, the largest demand of energy is in the form electricity. As one of the main global natural gas and oil suppliers and the third largest consumer of natural gas and oil in Southeast Asia, Malaysia has an abundance of non-renewable sources that can be used for the generation of electricity, particularly Peninsular Malaysia, Sabah, and Sarawak. In the past two decades, more than 90% of the electricity generated in Peninsular Malaysia has depended on non-renewable fossil fuels, such as coal, natural gas, and petroleum, and only 10% has been generated by renewable sources (Ahmad et al., 2017). Figure 1 shows the electricity generated by non-renewable sources in Malaysia.

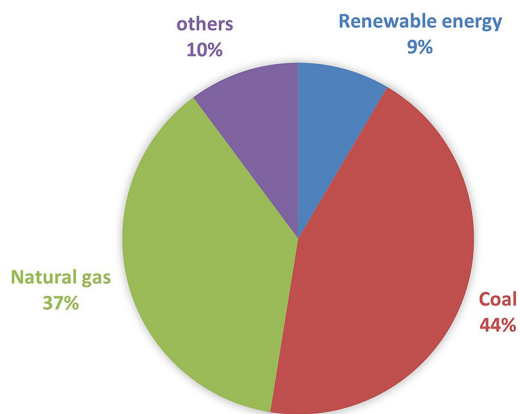


Figure 1. Electricity generation in Malaysia (Ahmad et al., 2017)

The massive development in this country, however, comes with good and bad consequences. One of the bad consequences is the depletion of domestic fossil fuels. Hence, to sustain the non-renewable sources in the country for future generations and to ensure a sufficient energy supply, Malaysia has imported resources from foreign countries. It has been reported that Malaysia has received coal from several countries, such as South Africa, Australia, and Indonesia. In 2012, the National Energy Security Conference estimated that 11.9 million tonnes of coal have been imported since 2009, and the amount increased steadily to 19.2 million tonnes in 2011 (Ahmad et al., 2017). Due to this concern, several policies and programmes have been introduced by Malaysia's government since 1979. Prior to the 1990s, the policies only focused on the depletion of natural resources and how to ensure a reliable supply of energy sources.

Later, in 2001, the Five-Fuel Policy was introduced, which was an improvement from previous policy (Four-Fuel Policy) (Mekhilef et al., 2014), and it encourages the utilisation of renewable resources. In 2011, a system called Feed-in-Tariff (FiT), which is monitored by the Sustainable Energy Development Authority of Malaysia (SEDA), was established (SEDA, 2012). Under this system, any individual or corporation can apply for a license to generate energy from renewable sources, such as hydro, solar, biomass, and biogas, and sell it as electricity. SEDA (2012) was also appointed as regulator agency when net energy metering (NeM) was announced by the Energy Commission in 2016. The difference between the old and new program is that power producers are allowed to consume the energy

generated and can sell the excess to the grid instead of selling it as electricity. As a result, public awareness of the depletion of natural resources has grown, and the interest in utilising alternative energy to reduce the dependency on fossil fuels has increased.

GENERATION OF ELECTRICITY

Energy generated by photovoltaic (PV) has attracted the public's attention. One reason for this is the strategic geographical location of Malaysia along the equator, which provides an abundance of sunlight and high solar irradiation. With around 12 h of daily sunlight, this country receives an average of 4.21–5.56 kWh/m² of solar irradiation, especially in Peninsular Malaysia (Ahmad & Mat Tahar, 2014). Conversely, Sabah, which is located in East Malaysia, has higher solar potential since this state has been found to receive the highest solar irradiation of approximately 18–24 kWh/m², followed by Sarawak with 14–16 kWh/m² (Ahmad & Mat Tahar, 2014). Consequently, this condition has caused many domestic and foreign investors to invest in the manufacturing industries related to solar power (Shafie et al., 2011). In addition, it also provides a better opportunity for Malaysia to devise the equipment associated with the solar generation of electricity. On the basis of the data recorded by SEDA in 2012, under the FiT system, 94% of applications have been approved for the installation of solar PV for power generation, and the remaining applicants have applied for biogas, biomass, and hydropower. Due to this, in 2017, Malaysia was announced as the world's third largest producer of solar power, particularly in the manufacturing of solar PV cells and modules. Another reason is because the production of electricity through solar technologies emits zero greenhouse gases to the atmosphere. Solar power is regarded as a clean technology for electricity generation.

At the same time, hydropower has become one of Malaysia's primary energy producers. According to the data presented by the International Energy Agency (IEA) in 2014, of the total energy consumption, 1% is supplied by hydropower. Meanwhile, natural gas still leads with 42%, followed by petroleum with 37% and coal with 17%, and the remaining 1% is from the summation of all renewable energy in Malaysia. The production of electricity using hydropower relies on two main factors: a sufficient amount of water

(Hussein & Nor Hamisham, 2016) and suitable terrain. Malaysia is characterized with especially high potential for the production of hydropower. Throughout the year, this country, on average, obtains 3549 mm of rainfall, and it has 189 named rivers with a total length of 57300 km, which has allowed Malaysia to increase its hydropower technologies. With a total of 3 hydroelectric power plants and 21 dams located in Perak, Pahang, and Terengganu, 1911 MW electricity are generated, whereas in the East Coast region, the largest hydroelectric plant is at the Bakun, Sarawak power station, with a capacity of 2400 MW. Apart from the availability of abundant source of water, hydropower is also favoured due to the potency for social and economic development of local communities, such as tourism and flood control.

In addition, Malaysia is concerned about the potential of biomass, since this source can commonly be found across the nation. Of the total area of 32.9 billion hectares, around 14.9% is used for the agricultural sector (Faisal et al., 2013) and about 60% is still natural forest. The major activities in the agricultural sector are oil palm plantation, which has become the largest source of biomass (Shamsudin, 2012), comprising around 43.7% of all biomass, forestry, which produces 30.56% of the biomass, rubber plantation, and last but not least animal farming. As the second largest producer and exporter of crude palm oil, the development of oil palm plantations is expected to expand in the coming years.

Originally, only a small portion of land was used for oil palm plantations, recorded at about 400 hectares in the year 1920. This increased to 5.0 million hectares in 2011 and is expected to grow to 5.2 million hectares in 2020. Approximately 50–70 tonnes of waste from the milling process are produced for 1 hectare of oil palm plantation. Biomass is a biological material, such as empty fruit bunch (EFB), mesocarp fibres, shells, and animal dung, which is mostly produced from agricultural activities. The generation of electricity is done by burning this source, and the energy produced is exactly the same as that produced from burning fossil fuels.

Despite the utilisation of renewable resources to reduce the reliance on fossil fuels resulting in successful outcomes, there are still adverse consequences. For example, although power generation by solar PV is regarded as the cleanest energy, deforestation is needed so that solar installation can be conducted. While installation on a

rooftop might help to avoid damage to the natural habitat, the high cost of the PV system still prevents Malaysia from implementing this technology. Furthermore, mismanagement of the system can cause environmental problems. Regardless of its undeniable potential for the generation of energy, hydropower plants may also give rise to serious ecological challenges, such as soil erosion and the disturbance of the ecosystem. Moreover, to enable the construction of dams and hydropower plants, the local population in the selected area may be required to migrate to a new location that is totally different from their old homeland.

Next, the environmental problems that arise once biomass is used for power generation cannot be neglected, even though the energy produced is most likely as high as when fossil fuels are used. During the burning of the materials, a number of harmful gases are also released into the atmosphere, such as methane gas, carbon dioxide, and other toxic gases. The emission of these gases has caused global warming, climate change, the greenhouse effect, and acid rain (Puan Yatim et al., 2016). In addition, there is uncertainty regarding the continuous supply of this source, since biomass also serves as an organic fertiliser and is used in the cement manufacturing industry.

It is necessary to discover the methods of energy generation through renewable resources. Moreover, it is also crucial to ensure that the energy sources satisfy certain criteria, namely that they are replaced naturally, have low risk, are inexhaustible, and are clean. Biogas is one type of alternative energy that matches most of the criteria listed. In general, biogas is produced via the anaerobic degradation of a material with high organic content, such as agricultural waste, food waste, and other sources. In conjunction with the Malaysian intention to reduce carbon emissions from 40% in the year 2020 to 45% in 2030 (Ahmad et al., 2017), biogas is a favourable choice, along with other alternative sources in Malaysia, due to the availability of its sources. It is estimated that around 17000 to 28500 tonnes of solid waste are produced every day, and 250 MW of power is generated. Even though biogas is known to generate electricity, it has not been fully exploited in Malaysia. One reason for this is the lack of reliable information regarding biogas. Therefore, this paper aimed to review the potentials and challenges of biogas production from different sources. The recent challenges for electrical energy generation from biogas were also discussed in this review.

CONCEPT OF BIOGAS

Biogas composition

Biogas is a flammable gas (Budiyono et al., 2018) that has a calorific value of 20–25 MJ/m³ (5.5–8 kWh/m³) (Sibiya et al., 2017). It has no odour and is colourless; however, it turns blue when burned (Christy et al., 2014). It consists of a mixture of gases, primarily methane (CH₄), carbon dioxide (CO₂), nitrogen (N₂), a small amount of hydrogen sulphide (H₂S), and other trace gases (Sawyer et al., 2019). Biogas is composed of 50–75% CH₄, 25–50% CO₂, 10% N₂, and 3% H₂S (Ramansu et al., 2016). However, the composition of each of these gases varies depending on the types of substrates used (Gashaw, 2016; Achinas et al., 2017). Besides substrates, parameters such as the volatile solid content, digester temperature, and C/N ratio also need to be considered (Budiyono et al., 2018). Last but not least, the biogas composition is also influenced by the operating conditions of the digester (Sibiya et al., 2017).

Metabolic pathway

The degradation of organic matter is a complex process involving the help of many groups of bacteria (Detman et al., 2018). This complex process comprises four steps, known as hydrolysis, acidogenesis, acetogenesis, and methanogenesis as shown in Figure 2. Hydrolysis is the first stage of anaerobic degradation, and it is a crucial step in degradation, since most of the organic substrates exist as large molecules that are not readily soluble (Ramansu et al., 2016). In this stage, complex organic substrates, such as carbohydrates,

proteins, and lipids, are converted into smaller units (Luo et al., 2019) by extracellular enzymes produced by several groups of hydrolytic microorganisms (Christy et al., 2014). These microorganisms will first form bacterial colonisation over the substrate surface, followed by the secretion of different enzymes depending on what type of substrate is used, such as cellulase, protease, and lipase (Christy et al., 2014), which bind to large molecules and transform the substrates into simpler forms (Ramansu et al., 2016). For instance, complex carbohydrates are converted into glucose, proteins are converted into amino acids, and lipids are hydrolysed into glycerol and long-chain fatty acids (LCFAs) (Anwar et al., 2011).

After enzymatic cleavage, the hydrolysis products, which are now able to diffuse through cell membranes (Meegoda et al., 2018), further undergo fermentation by acidogens (Anwar et al., 2011) to produce organic acids, such as acetic acid, propionic acid, amino acid, and butyric acid (Meegoda et al., 2018), and other metabolites, such as alcohols (Sibiya et al., 2017). The production of various organic acids is affected by several factors, such as the existing microbial species and the condition of the reactor itself (Sibiya et al., 2017). In addition, acidogenesis products can be formed through many metabolic pathways (Luo et al., 2019). The stage after acidogenesis is acetogenesis or the dehydrogenation stage (Anthony et al., 2019). Common substrates for the acidogenesis phase are volatile fatty acids (VFAs), alcohols, amino acids, and aromatic compounds (Ramansu et al., 2016), while the products formed are hydrogen (H₂), carbon dioxide (CO₂), and acetic acid (Jorge & Alberto,

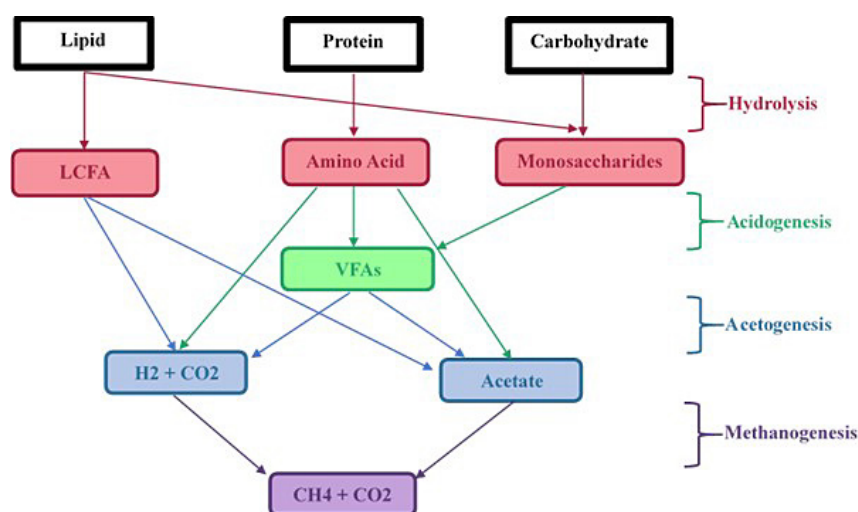


Figure 2. Metabolic pathway (Christy et al., 2014)

2012). This stage is commonly regarded as thermodynamically unfavourable (Jorge and Alberto, 2012). However, this issue can be overcome if the hydrogen partial pressure is kept low.

The final stage of anaerobic degradation is methanogenesis, where, at these points, methanogens grow slowly and become sensitive to environmental changes (Jorge and Alberto, 2012). In this stage, the microorganism involved in the process can be divided into two groups, known as aceticlastic and hydrogenotrophic methanogens (Jorge and Alberto, 2012). In general, methanogenesis has six major pathways; however, the most common pathways are aceticlastic and hydrogenotrophic methanogenesis (Ramansu et al., 2016). Aceticlastic methanogenesis, or the formation of methane by the utilisation of acetate, accounts for 2/3 of the production, while the remaining is produced through the utilisation of H₂ (Meegoda et al., 2018). Thus, it can be concluded that each stage of anaerobic degradation is conducted by different groups of microorganisms (Jorge and Alberto, 2012). In addition, each stage requires different conditions; for example, the acidogenesis phase prefers a slightly acidic environment (Christy et al., 2014), while in methanogenesis, an alkaline condition is favoured by the methanogens (Zhang et al., 2014).

Microorganisms capable of producing biogas

Anaerobic digestion is a biological process that involves living organisms producing desired products through a series of steps, including assimilation, transformation, and decomposition of organic material (Jorge and Alberto, 2012). In general, there are a number of different species of microorganisms that participate in the digestion of complex molecules into simple molecules. Anaerobic digestion consists of four stages, each involving different species of microorganisms and different metabolites. Basically, different species of microorganisms can be categorised to four groups according to their functionality. Table 1 lists the microbes that are involved in each stage of anaerobic degradation.

Group one bacteria are responsible for the hydrolysis of complex organic matter, such as carbohydrates, proteins, and fats, into their simple soluble products (Jorge & Alberto, 2012). Streptococcaceae and Enterobacteriaceae are examples of a family belonging to this group. In the acidogenesis stage, intermediate products such organic

Table 1. Microorganisms involved in biogas production

Stage	Microorganism	Reference
Hydrolysis	<i>Clostridia</i> <i>Micrococci</i> <i>Bacteriodes</i>	Christy et al., 2014
Acidogenesis	<i>Enterobacterium</i> <i>Acetobacterium</i> <i>Eubacterium</i>	Ramansu et al., 2016
Acetogenesis	<i>Acetobacterium woodii</i> <i>Clostridium Acetilicum</i>	Jorge and Alberto, 2012
Methanogenesis	<i>Clostridiales</i> <i>Halanaerobiales</i> <i>Thermoanaerobacteriales</i>	Detman et al., 2018

acid are utilised by hydrogen-producing aceto-genic bacteria and converted to acetate, H₂ and CO₂. In this stage, this group of bacteria must be co-cultured with hydrogen-consuming bacteria to allow the conversion. Next, the process involves the conversion of metabolites into the final product of this stage: acetate. This can be done by two types of bacteria: autotrophs and heterotrophs. Autotrophs utilise CO₂ and H₂ as the carbon source, while heterotrophs use an organic acid, such as formate and methanol, to produce acetogen. In the last stage, Methanogens are the bacteria responsible for methane production. This group can be found abundantly in lake, swamp, as well as organic matter where the environmental conditions are mostly anaerobic (Jorge & Alberto, 2012).

Substrates used to produce biogas

Through human activities, a wide range of waste streams are generated, which can be used as feedstock for biogas production (Horvath et al., 2016). One of the reasons why waste is selected as feedstock is that it usually has high organic content, such as carbohydrates, proteins, fats, cellulose, and hemicelluloses (Achinas et al., 2017), which can be used as substrates for biogas production (Sawyer et al., 2019). Besides, the utilisation of waste in anaerobic digestion from many sectors might help to control environmental problems (Jorge & Alberto, 2012; Arij et al. 2018). In general, all waste streams can be classified into several groups, known as agricultural waste, organic municipal solid waste (MSW), and organic, industrial, and commercial effluents (Atelge et al., 2018). These waste streams are categorised based on the origin of the waste itself. For instance, animal manure and crop residues are grouped into agricultural waste, since both types of waste are from the same background (Sibiya et al., 2017).

Meanwhile, food and beverage waste, waste from slaughterhouses, dairy waste, and other types of waste from the processing industry are included in organic, industrial, and commercial waste (Sibiya et al., 2017). Last but not least, waste such as sewage and the organic fraction of MSW are categorised into organic MSW (Sibiya et al., 2017).

In general, agricultural waste can be defined as a by-product of the agricultural sector, which may contain the material that can be exploited for beneficial use (Obil et al., 2014). One way of utilising agricultural waste is to use it as a substrate for the production of biogas. This is because agricultural waste, which comprises animal waste, crop residues, and fruit and vegetable waste, is made up of components such as carbohydrates, proteins, fats, cellulose, and hemicellulose. These components are important criteria in selecting the substrate for biogas production (Olvera & Alberto, 2012). The composition of these types of waste may vary according to the types of activities and system used, and the waste can be attributed to several categories, such as liquid, slurries, and manure.

In the agricultural sector, animal manure can be regarded as one of the largest sources of organic waste (Sibiya et al., 2017). Animal manure contains high organic content, and it can be a beneficial resource, especially for anaerobic digestion (Toma et al., 2016). Furthermore, the use of animal manure will also help to reduce environmental problems, such as reducing greenhouse gas emissions (Zahariev et al., 2014). Moreover, the end product of anaerobic digestion (AD) can be used as a fertiliser, and it also helps to reduce odour (Sebola et al., 2014). Basically, manure from different animals is commonly used as biogas substrates (Osama, 2019), and each of them have their own properties (Sibiya et al., 2017).

In addition, the C/N ratio is an important factor that affects biogas production. This is because the production of biogas is highly controlled by the C/N ratio (Abebe, 2017) in the feedstock. However, in manure of certain animals, the C/N ratio is around 6–8, such as in pig slurry (Toma et al., 2016). A low C/N ratio in the feedstock of the anaerobic digester may cause insufficient biogas production. In the anaerobic digester, the recommended C/N ratio of the feedstock is in the range of 20–30 in order to ensure a sufficient amount of nitrogen for the process (Gashaw, 2016). On the other hand, a high C/N ratio indicates that there is rapid consumption of nitrogen by methanogens, resulting in lower biogas yield (Armah et al., 2017). One way to improve

the biogas yield is by mixing or co-digesting the animal manure with other substrates (Sibiya et al., 2017). One advantage of co-digesting is that it provides balanced nutrients to the anaerobic digester (Osama, 2019). Apart from that, co-digesting also helps to reduce the risk of ammonia inhibition and acidification (Toma et al., 2016).

Next, when selecting substrates for biogas generation, the main considerations are the sustainability, energy, as well as environmental and economic values of the substrates (Bharathiraja et al., 2018). Besides animal manure, MSW is a potential source for recovering energy (Sebola et al., 2016). Under MSW, food waste, such as raw food materials, food residues from households and restaurants, and fruit and vegetable waste, can be considered the main component (Luo et al., 2019; Sebola, et al., 2016). This type of waste can cause deterioration of land and water, causing a foul smell and threatening the life of humans, plants, and aquatic animals, and it can cause other serious environmental problems if not treated properly (Muhammad & Torii, 2015; Shivanil & Bashir, 2018). However, the digestion of food waste will produce a high concentration of VFAs due to rapid acidification. An accumulation of VFAs will lead to a drop in the pH, which eventually reduces the methanogenic activity (Abebe, 2017). This is because, in general, most anaerobic bacteria, including methanogens, function at a pH level in the range of 5.5–8.5 (Abebe, 2017).

Beside agricultural waste, palm oil mill effluent (POME) is one of the best substrates for utilisation in biogas production. One of the advantages of using POME as a substrate is that it contains high organic content, which is beneficial for the production of biogas (Ji et al., 2013). This type of waste is produced during the extraction of palm oil from fresh fruit bunch (FFB) (Abu Bakar et al. 2018).

Biogas applications

Currently, biogas can be applied in many areas, regardless of its scale. While the application of biogas on a large scale is preferred in a developed country, the small scale is more popular in a rural area (Alexander et al., 2019). In general, biogas can be utilised for electricity generation, and cooking. For example, most biogas produced in Europe is used for the generation of heat and electricity (Horvath et al., 2016). The development of biogas for different applications is attractive,

especially when the origin of the source is taken into consideration. The consumption of this gas will also minimise the possibilities of this gas being released into the atmosphere, particularly during the waste treatment process. This is because most industrial producers, such as those from the crude palm oil manufacturing industry, only want to meet one of the regulations stated by the Department of Environment (DOE), which is the biochemical oxygen demand (BOD) limit. There is no entrapment of methane gas produced during anaerobic digestion, and, hence, this action causes a significant amount of environmental problems, such as climate change, the greenhouse effects, and global warming. Fortunately, the public awareness of these environmental problems has increased, thus causing many producers to exploit these renewable energies for use in various applications. One application is the generation of electricity. There are many countries in the world that still encounter uncertainty in their energy supply. For instance, countries such as Togo and most of the West African countries are facing this problem, which suppresses development in many sectors across their nations (Azouma et al., 2018). Hence, biogas production has become an interesting option for people, particularly those in the countries that have an unreliable supply of electricity, since they can exploit the waste from animals, agriculture waste, or waste generated by themselves.

CHALLENGES OF BIOGAS PRODUCTION

Inoculum used

Biogas is a product generated from the degradation of substrates by various microorganisms. These microorganisms can exist in different ranges of shape, size, and growth phase (Jyotsana & Srivastava, 2007). In biogas production, microbial populations are provided in the form of an inoculum. An inoculum is a biologically active liquid that is rich in microorganisms (Dennis, 2015). In addition, an inoculum not only provides the microbial population but also serves as a source of micronutrients in the anaerobic digester (Asad and Zeshan, 2019). Furthermore, in some cases, the absence of an inoculum could cause reactor failure (Asante-Sackey et al., 2018). There are several advantages of using an inoculum in biogas production. Firstly, it provides the initial microbial population (Senes-Guerrero et al., 2018).

Secondly, the digestion of the substrates with the inoculum will increase the production rate and the efficiency of anaerobic digestion (Dennis, 2015). Furthermore, the inoculum helps to shorten the starting time of the microbial community in the digester (Yu et al., 2014) and ensures the stability of the process (Horvath et al., 2016) by providing a sufficient buffering capacity (Yu et al., 2014).

The most important aspect of the inoculum is its enzymatic activity and nutrient content (Yu et al., 2014). As the enzyme producer, microorganisms influence the enzymatic activity in the digestion process (Yu et al., 2014). To ensure a sufficient level of microorganism activity, the selected inoculum must be fresh, homogenous, and have wide microbial diversity (Vrieze et al., 2015). High enzymatic activity could lead to a higher biogas yield. Conventionally, animal manure and sludge from wastewater are the most popular inoculums that have been used in biogas generation (Senes et al., 2019). Sludge is often selected as an inoculum because of its availability and uniform properties (Raposo et al., 2006). However, the biogas yield is higher and steadier when animal manure is used as an inoculum, compared to waste sludge (Asad & Zeshan, 2019).

The varying biogas yields of different inoculums might be due to the microorganism activity and their degradation efficiency. (Yu et al., 2014). The adaptation of microorganisms towards substrates is one of the factors that influence the microorganism activity (Yu et al., 2014). The higher the microorganism activity, the faster it can adapt to the substrate. Next, the adaptation of microorganisms to substrates depends on the origin of the population (Vrieze et al., 2015). Another important characteristic of the inoculum that helps to enhance biogas production is its micro- and macronutrient content (NREL, 2017). For instance, the inoculum helps to provide nutrients, such as nitrogen, to the substrates that have low nutrient content.

There are several studies have been conducted to investigate the effect of inoculum from different sources for biogas production as shown in Table 2. A study shows that the biogas produced in a reactor with the presence of digested manure and acclimatized sludge yield higher biogas, compared to the biogas produced by inoculum from septic tank sludge. Lower biogas yield is due to accumulation of VFA where it is only partially digested by septic tank sludge. In turn, higher biogas yield indicated that inoculum provides initial

Table 2. Sources of biogas for biogas production

Inoculum source	Substrates	References
Cow dung	Sheep paunch manure	Lawal et al., 2016
Cattle manure	Waste from medical cotton industry	Ismail and Talib, 2016
Municipal waste treatment plant	Cow dung slurry	Singh et al., 2010
Treating stillage from ethanol plant	Cellulose and basic anaerobic medium	Han et al., 2015
Septic tank sludge	Sunflower meal and wheat straw	Rajput and Sheikh, 2019
Anaerobic sludge	Food waste	Liu et al., 2009

microbial population and sufficient buffering capacity (Rajput & Sheikh 2019). A different study also shows that inoculum source has a significant effect on biogas production. This is because inoculum generally had more diverse microorganisms to degrade different or complex substrates and efficient biogas production can be obtained with various microbial community patterns. In this study, different inoculum sources were investigated, including digested manure, raw cattle manure, treated cattle manure, digested stillage from CSTR (Han et al., 2015). It was found that biogas produced from inoculum digested stillage is lowest compared to other options. It is suggested that microbial communities are special for degradation of certain cellulose.

Substrates pretreatment

There are many factors that are taken into consideration during the selection of substrates for biogas production. One factor is that the chosen substrates must contain high levels of degradable organic content (Saifuddin & Fazlili, 2016). Examples of substrates that are frequently chosen are agricultural residues (Muda et al., 2016; Kamarudin et al., 2018), agricultural crops (Ahmed et al., 2015; Salihu & Alam, 2016; Sabri et al., 2018), and industrial wastewater (Saifuddin & Fazlili, 2016). However, biogas production through the degradation of this organic material by microorganisms under anaerobic conditions often produces low

yield (Alam & Abdul Hamid, 2017). This is because the substrates used in biogas production are comprised of very stable complex molecules, such as lignocellulose (Wagner et al., 2018).

The major components of lignocellulose are cellulose (30–50%), hemicellulose (25–30%), and lignin (10–35%) (Hossain et al., 2019). Lignin, one of the main components of lignocellulose, is a complex polymer that functions as a barrier to prevent access to carbohydrates (Tawaf et al., 2019), and this is also the reason why hydrolysis is considered a rate-limiting step (Deepanraj et al., 2017). A major challenge in the utilisation of lignocellulosic feedstock in the fermentative process is the transformation of complex polysaccharides into simple sugars (Armah et al., 2017). Hence, pretreatment of substrates is one possible way to enhance the degradation process (Deepanraj et al., 2017).

The aim of any pretreatment is to ensure that the nutrients contained in the substrates can be utilised by the microorganism to produce biogas (Salihu & Alam, 2016). Biodegradability is an important key to evaluating the effectiveness of pretreatment (Saifuddin & Fazlili, 2009). There are many different pretreatments that are group into several categories, such as mechanical pretreatment, thermal pretreatment, chemical pretreatment, and biological pretreatment (Zhang et al., 2014). According to a study, mechanical pretreatment is the most common pretreatment for the substrates used in biogas production. It is estimated about 33% of mechanical pretreatment was applied, then followed by thermal pretreatment with 24%, chemical pretreatment with 21% and remaining percentage combination of two or more pretreatments (Salihu & Alam, 2016).

Table 3 shows the categories and examples of pretreatments. Ultrasonication is one type of mechanical pretreatment that has been found to be efficient at releasing extracellular substances (Saifuddin & Fazlili, 2009) resulting from cell disruption due to sludge disintegration (Mohammad et al., 2008). There are several processes involved in this technique, which include radical, shearing,

Table 3. Categories and types of pretreatment

Category	Pretreatment type	Reference
Mechanical	Ultrasonication, coalescer filtration	Deepanraj et al., 2017; Yaeed et al., 2017
Thermal	Microwave irradiation	Saifuddin and Fazlili, 2009
Chemical	Alkali acid	Montgomery and Bochmann, 2014; Mahmud et al., 2017
Biological	Enzymatic biofilm microbial	Alam and Abdul Hamid, 2017

pyrolysis, and combustion processes (Salihu & Alam, 2016). It is assumed that several factors, such as ultrasonic density and intensity, influence disintegration (Mohammad et al., 2008). The high intensity of ultrasonic waves creates a mechanical shear force (Deepanraj et al., 2017), which is believed to help in cell lyses. In addition, ultrasonic intensity is not the only important parameter of this method. According to a study by Saifuddin & Fazlili (2009), the sonication time also plays an important role in ultrasonication, which eventually leads to a better digestion process.

Besides mechanical pretreatment, biological pretreatment has also been shown to aid in biogas production (Lin et al., 2010). This is because the biological pretreatment method requires low energy consumption (Bremond et al., 2018), a lower cost is needed for this treatment (Bremond et al., 2018), and no chemicals are required during treatment of the substrates (Mohammad, et al., 2008). Furthermore, this pretreatment reduces the formation of inhibitory products (Wagner et al., 2018). Biological pretreatment of substrate requires the presence of microorganisms that will help to disrupt the substrate structure itself (Lin et al., 2010) since they will degrade lignin and hemicelluloses (Mohammad et al., 2008) by producing an enzyme to degrade lignin. The conversion of lignin in nature is commonly carried out by white rot fungi (Wagner et al., 2018) since this type of fungi is capable of producing lignin peroxidase (Lip) and laccase (Lac) (Lin et al., 2010), two enzymes that play an important role in lignin degradation (Tawaf et al., 2019). Examples of white rot fungi are *Phanerochaete chrysosporium*, *Trametes versicolor* (Wagner et al., 2018), *Ceriporiopsis subvermispora*, *Pleurotus ostreatus* (Mohammad et al., 2008), and *Pleurotus florida* (Zhang et al., 2011). However, researchers have also reported that several bacteria are capable of producing the enzymes that can degrade lignin, such as *Bacillus* sp. (Tawaf et al., 2019) and *Sphingomonas paucimobilis* (Mohammad et al., 2008).

Chemical pretreatment is one of the approaches aimed at breaking down the cellular structure of biomass and to increase specific surface area for biogas production (Ali & Sun 2015). This type of pretreatment is usually used for lignocellulosic substrates. This is because the structures and compositions of lignocellulosic materials make it very resistant towards hydrolysis (Bochmann & Montgomery 2013). Changing the structure of lignocellulose, such as

reducing the crystallinity of cellulose, will result in increasing degradability of substrates (Ali & Sun 2015). Chemical pretreatment uses different types of chemicals, mainly acids and bases with different strength and condition (Bochmann & Montgomery 2013). Alkali pretreatment is a process to increase the biodegradability of substrates where the presence of acetate group in the hemicellulose is removed in order to make hemicellulose is more accessible to hydrolytic enzyme (Bochmann & Montgomery 2013). Addition of alkaline solution also helps to cause swelling of lignocellulose. Removal of lignin from lignocellulosic also constitutes one of the main effects from this treatment (Cater et al. 2014). Several alkaline solutions such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are usually chosen in the process (Bochmann & Montgomery 2013). Besides alkali, acid solution is also one of agents for hydrolysis of cellulose. It assists in insolubilising lignin and hydrolyze hemicellulose. However, the use of acids such as nitric acid gives low production of biogas because another gas is produced, such as sulphide and nitrite ion. Furthermore, strong acid will lead to excessive degradation of complex substrates (Venturin et al. 2019). In turn, the disadvantage of alkali pre-treatment is that it leads to increase of pH, which eventually inhibits methane formation. Furthermore, chemicals pretreatment is expensive and less environmentally friendly due to the usage of several chemicals during the pretreatment process (Cater et al. 2014).

Technology used to produce biogas

There are many different types of anaerobic digesters that are used around the world. The system used to produce biogas should not be complex and should be easy to operate. (McCabe & Murphy, 2018). In general, digesters can be classified into two types, known as wet digesters and dry digesters (He et al., 2011). A wet digester is a system in which the concentration of total solid is less than 10–15% while dry digester is a system with the concentration of total solid higher than 15–20% (Fardin et al., 2018). There are many types of digesters that is used in biogas production such as continuous stirred tank reactor (CSTR), plug flow reactor (PFR), fixed-bed reactor (FBR) up flow anaerobic sludge (UASB) expanded bed reactor (EBR) and anaerobic filter reactor (AF) (He et al., 2011).

The continuous stirred tank reactor (CSTR) is the most common technology that has been applied to industrial biogas production (Fu et al., 2010). This system has been widely used for substrates with high moisture content, such as agricultural and industrial wastewater, manure, sewage sludge, and MSW (Fu et al., 2010). This technology is the least expensive and has the simplest design compared to other technologies (Berni et al., 2016). In addition, the CSTR also often yields high amount of methane (Fu et al., 2010). Furthermore, the CSTR technology offers similar conditions as the anaerobic environment, since this technology is a product derived from an anaerobic pond (Berni et al., 2016). Besides, this technology is applicable for use in all temperature ranges (McCabe & Murphy, 2018).

Next, the second most commonly used technology is the up-flow anaerobic sludge blanket (UASB) reactor. In this technology, substrates such as wastewater enter from the bottom the reactor and flow upward through the sludge blanket, which consists of biologically activated sludge in the form of a granular sludge bed. The configuration of the UASB allows for efficient mixing of biologically activated sludge and substrates, thus enabling rapid anaerobic degradation to produce biogas (Mainardis et al., 2020). This technology has many advantages: it requires a small amount of land, it has low operating and construction costs, and it has uncomplicated maintenance. However, there are drawbacks to the UASB technology. One drawback is that it is not efficient for high strength wastewater due to incomplete biodegradability that leads to lower biogas production (Daud et al., 2018). Insufficient circulation of biogas in the reactor will result in insufficient support for the formation of granules. Besides, the generated biogas also facilitates the mixing of substrates and activated sludge (Mainardis et al., 2020).

Another common digester that is used in biogas production is a plug flow reactor (PFR). PFR is a lowrate digester where this digester can be operated with total solid concentration is less than 15% (Fardin et al. 2018). This is due to how this digester works where there is no longitudinal mixing of substrates from inlet to outlet (Mutungwazi et al. 2018). The advantages of PFR involves easy installation and handling, very low capital cost and a very simple design. However, the drawbacks of this digester include lack of agitation involved in this

system; hence, it leads to slow solid conversion and consequently low biogas production (Mutungwazi et al. 2018).

A fixed-bed digester (FBR) is one of popular types of digesters for the reaction involving solid substrates (Dhiyani & Bhaskar 2019). In this system, fluidized medium – usually liquid or gas – is passed through solid substrates with high velocity to suspend the solid resulting in high solid-liquid specific interfacial contact area which eventually reduces resistance to mass transfer (Wang & Zhong 2007). The advantages of FBR are that it offers lower operating costs and higher efficiencies (Hafeez et al. 2019). On the other hand, the disadvantage of FBR is that it often accumulates stagnant gas pockets in which causes gas flooding and poor liquid distribution (Wang & Zhong 2007).

An anaerobic filter (AF) digester is a system that consists of fixed bed (Bhattacharya et al. 2018) where it provides an attachment surface for anaerobic bacteria in the form of biofilm (Anderson et al. 2003). The support media used can be in term of any material, such as plastics, granular activated carbon (GAC), sand, reticulated foam polymers, granite and stone (Anderson et al. 2003). The anaerobic bacteria that are attached on fixed bed will decompose any substrates that come in contact with it in which will produce desired product (Bhattacharya et al. 2018). However, there is one limitation of this digester, which is accumulation of non-biodegradable solid on bed structure that will cause the failure of fixed bed. Hence, the usage of this digester is limited to the substrates with low solid content. Furthermore, this digester requires high costs relative to the material that is selected for fixed bed (Anderson et al. 2003).

Factors affecting biogas production

Methanogens are very sensitive to the changes that happen under anaerobic environmental conditions (Jorge & Alberto, 2012). A slight change in any parameter will result in the inhibition of the methanogenic activity. Therefore, it is crucial to ensure the methanogens in anaerobic system are well maintained through the control of the environmental condition. In general, there are several parameters that control the anaerobic system, such as temperature, organic loading rate (OLR), pH and alkalinity, heavy metal, and substrate concentration (Jorge & Alberto, 2012).

Temperature

Temperature is a parameter that plays an important role in AD, since it controls methane yield, stability, the microbial community (Azeem et al., 2011), and the effectiveness of the enzymatic reaction (Zhang et al., 2014). The anaerobic reaction can be performed in a wide range of temperatures due to the ability of anaerobic bacteria to grow at different temperatures (Zhang et al., 2014). Typically, there are three possible temperature ranges, known as psychrophilic, mesophilic, and thermophilic (Rameshprabu & Yuwalee, 2016). The table below shows the ranges of temperatures for different conditions. However, the most common conditions preferred in anaerobic digestion are mesophilic and thermophilic (Yee et al., 2017). In addition, it has been reported that microbes are most active during mesophilic and thermophilic reactions (Gashaw, 2014).

In general, a high temperature will speed up the reaction involved in a chemical process. This suggested anaerobic digestion under a thermophilic reaction has several advantages compared to the mesophilic and psychrophilic conditions. One of the advantages of the thermophilic condition is degradation of LCFA, VFA and other intermediated products (Chiu & Lo, 2016). Moreover, greater amount of biogas is produced when the operation is done under thermophilic conditions (Ohimain & Izah, 2017). A study performed by Pandey & Soupir (2012) showed that apart from a higher biogas production rate, biogas produced is also faster under thermophilic conditions. A similar result was obtained in a study performed by Ghatak & Mahanata (2018) where it was concluded that better biogas was produced more quickly under the thermophilic conditions. In addition, rapid digestion of substrates helps to reduce the hydraulic retention time (HRT) (Shi et al., 2016). Another advantage is that the death rate of pathogenic bacteria increases along with the temperature, especially during a thermophilic reaction (Kumar et al., 2013).

However, the digestion of substrates under the thermophilic condition has some drawbacks. One drawback is that the rapid chemical reaction will result in the accumulation of VFA in which eventually lowering biogas yield (Azeem et al., 2011). A study by Komemoto et al. (2009) stated that a low biogas production rate was observed throughout an experiment despite the high solubility of substrates during the early stage of the

experiment. In addition, a process also requires higher energy consumption to operate at higher temperatures (Shi et al., 2016). Another disadvantage is that the process is harder to control under the thermophilic conditions (Hagos et al., 2016): a significant change during the process, even 1°C, will disrupt the growth of methanogenic bacteria, since they are very sensitive to sudden changes in the surrounding temperature (Yatvika et al., 2004).

Even though the biogas produced under the mesophilic condition is relatively low, the microorganism activity is high, and it contributes to the substrate solubility performance (Komemoto et al., 2009). A study of the effect of temperature on solubilisation by Komemoto et al. (2009) showed that substrate solubility was higher at temperatures within the range of 25°C to 45°C, which also indicates good microorganism activity. Besides, a stable anaerobic process can be reached when the process is conducted under mesophilic reactions (Rameshprabu & Yuwalee, 2016). In addition, when the operation is stable, diverse microbial communities can be found in the bioreactor (Yee et al., 2016). Furthermore, it has been reported that the biogas produced under mesophilic condition produced less percentage of carbon dioxide (Sorathia et al., 2012). Another advantage is that the temperature range of the mesophilic conditions is also the optimum temperature range for methanogenic bacteria to operate, which is between 33°C and 35°C (Gashaw, 2014). Below this range, the production of biogas will be lower, while temperatures above this range will inhibit activity of the biogas-producing bacteria (Komemoto et al., 2009).

Volatile fatty acid (VFA)

Beside temperature, an organic acid known as a VFA is one factor that can influence the bacterial community in an anaerobic digester (Franke-Whittle, 2014). This component is an essential intermediate that is produced during acidogenesis (Lukiyawesa et al., 2020) by acidogenic bacteria (Franke-Whittle, 2014). In this stage, the organic material from the previous process is converted by acidogenic bacteria through the fermentation process. From this process, several organic acids are formed, such as acetic acid, propionic acid, lactic acid, and succinic acid (Osama, 2019).

Among the VFAs, acetic acid is the most common intermediate, since it is directly related to CH₄ and CO₂, the end products of anaerobic digestion (Lee et al., 2015). The presence of this

intermediate will determine the operating conditions in the digester, such as the pH (Zhang et al., 2014). The accumulation of VFAs like propionic acid, which is the most toxic compared to other VFAs (Luo et al., 2019), at a higher rate commonly results in a decreasing pH value (Dobre et al., 2014). Consequently, any significant changes in pH will also effect the growth of microorganisms (Gashaw, 2014). For example, the methanogenic activity is inhibited when the pH is below 6.5 (Gashaw, 2016). Hence, it also causes deterioration in the performance of the digester, which, in the end, negatively impacts the production of methane gas (Franke-Whittle et al., 2014).

Hydraulic retention time (HRT)

The HRT is the average amount of time that substrates are retained in the digester for a given volume. A certain retention time is determined to ensure that the substrates are in contact with the microbial population (Shi et al., 2016; Pramanik et al., 2020). In general, a long HRT is required for the digestion of substrates containing complex compounds, such as lignocellulose, while a relatively shorter HRT is needed for the substrates that can degrade easily (Shi et al., 2016). The HRT also depends on the types of substrates used since some of the substrates are composed of lignocellulosic waste. There are some advantages and disadvantages of shorter and longer HRTs. The first advantage of a longer HRT is that the biogas produced in an anaerobic digester is greater than the amount of biogas produced with a shorter HRT. This is because increasing the retention time of the substrates with the microbial population will provide a sufficient contact time, thus allowing for degradation of the substrates and ensuring that the substrates are fully utilised (Alepu et al., 2016; Musa & Idrus, 2020). Furthermore, a shorter HRT leads to methanogen washout and the accumulation of VFAs in the digester, eventually causing a decrease in pH (Alepu et al., 2016). However, a longer HRT is more costly compared to a shorter HRT. One way to reduce the HRT is to apply pretreatment to the substrates to enhance the digestion process.

pH

Besides temperature, there are several parameters that can influence the digestion activity in an anaerobic digester. One of the parameters is pH, which is controlled by the alkalinity produced by

the substrates. In general, the alkali generation is due to hydroxides and carbonates of existing metals in the substrates, such as calcium, magnesium, sodium, potassium, or ammonia (Jorge & Alberto, 2012). Hydroxides and carbonates act like a buffer to control the environment of the digester to ensure that the condition is favoured by the microorganisms. This is because the accumulation of VFA during acidogenesis will increase the acidity of the substrates. Moreover, a slight change in the number of species of microbes in the mixed population can modify the pH (Hu et al., 2004).

One the other hand, enzymatic activity is severely influenced by pH, since different enzymes only function under specific conditions (Lay et al., 1997; Pramanik et al., 2019), and this explains why each stage of anaerobic digestion requires a different pH range. For the hydrolytic stage, the optimum pH is between 5 and 6, while for methanogenesis, the pH value is between 5.6 and 8. It has been found that the inhibition of methanogenesis occurs when the pH value is above 8 (Jorge & Alberto, 2012). One way to reduce inhibition is to dilute substrates with water, as mentioned in a previous study (Lay et al., 1997).

Other parameters

Other parameters, such as heavy metal concentration is among the parameters that are responsible for the digestion process. A certain amount of heavy metal will help the growth of microorganisms since the heavy metal acts as a nutrient; however, if the concentration of the heavy metal is too high, this will cause toxic conditions in the digester (Jorge & Alberto, 2012). This is because heavy metals will disturb the hydrolysis process, since they can bind to the SH group of enzymes (Shi et al., 2017).

Technological challenges of the generation of electricity from biogas

Combined heat and power (CHP) engines

Nowadays, power generation using renewable sources is more focused due to several factors, such as sustainability, security, and reliability of energy supplies. In addition, energy generation using renewable sources seems to be a better solution to address the environmental issues that have been around for decades (Shafie et al., 2011). This is because the renewable energy will reduce the negative impact on the environment. For instance,

the utilisation of biogas for electricity generation mitigates the emission of greenhouse gases into the atmosphere, since it is regarded as clean energy (Fantozzi & Buratti, 2009). Furthermore, the generation of biogas usually takes place by utilisation of substrates that are recovered from waste, which, in return, will reduce pollution (Jorge & Alberto, 2012).

Combined heat and power (CHP) is an integrated system that simultaneously produces electricity or mechanical power and useful thermal from a single energy input (NRDC, 2013). The principle of this system is derived from the combustion of coal to produce steam, and the steam produced is then converted into mechanical power in a steam engine (Kalam et al., 2012). This system can be used in many different setups and different range scales, ranging from micro to small scale (residential) and to large scale (industrial scale) (EESI, 2013). Commonly, the CHP system operates in two ways, known as topping and bottoming cycles (US Department of Energy, 2015). The topping cycle is used primarily to generate electricity through a turbine or reciprocating engine, microturbine, and fuel cell, and recovered heat is used to supply the heating or cooling process, while the bottoming cycle produces heat first for the industrial process, which requires a sufficiently high temperature (Kalam et al., 2012). Table 4 shows the heat engine or CHP prime movers of a different technology. Besides heat engines, auxiliary equipment, such as a pump for circulating heat transfer fluid and a fan for auxiliary rejection, are often included in the system (NREL, 2017).

The CHP system represents a versatile technology that can provide several advantages in terms of efficiency, reliability, cost, and environmental impact for end users (NRDC, 2013). The major benefit of using the CHP system is the potential to increase the efficiency for both electricity and heat generation. Compared to the electricity and heat production by fossil fuel power plants, the efficiency of a

CHP system can increase from 33% to 75%, while a fossil fuel power plant wastes two thirds of its energy, which means that less fuel is consumed to generate energy. From an environmental perspective, energy generation using less fuel will help to decrease environmental impacts, such as reducing air pollution caused by greenhouse gases (GHGs) and other emissions (CCAP, 2013; EESI, 2013). In addition, a CHP system can reduce costs. This is because the generation of energy and power onsite can reduce the overall expenditure by nearly one third to one half (NRDC, 2013).

In the CHP system, both renewable resources and fossil fuel resources are used to generate energy. The most common type of fuel is natural gas; however, there is also potential for renewable energy, such as biogas, to be utilised (US Department of Energy, 2017). There are various available technologies that can convert biogas to electricity. In general, there is a series of steps involved during the conversion of biogas to electricity. The first step is the generation of chemical energy through the combustion of biogas. The chemical energy produced is then converted into mechanical energy by an engine system in a control combustion system. Lastly, mechanical energy will activate the generator to produce electrical power (Sacher et al., 2019). For electricity generation from biogas, the heat engines that are typically used are a gas turbine and combustion engine. A gas engine is preferred for the small scale, since it is cost effective compared to the gas turbine; however, in terms of efficiency in producing electricity, the gas turbine is favoured.

CHP is an example of gas turbine technology. CHP is an energy generation system that is currently providing an interesting opportunity in terms of power production and consumption effectiveness. This system promotes large annual savings. A number of CHP technologies are being developed each day. There are two common parameters used to evaluate the performance of CHP, which are the efficiency of the product generated and the power to heat ratio. Combustion-producing steam and steam turbines are the most common technologies chosen for large-scale and small-scale CHP systems. At the same time, the combination of combustion-producing steam with ORC in a small-scale CHP system is receiving more interest due to several reasons. One reason is that the ORC system is feasible compared to the Stirling engine. This system is estimated to yield 60% less than the system used by the Stirling

Table 4. Types of heat engines of different technologies

CHP prime movers	Power range	Reference
Internal combustion range	Smaller than 5 MW	NREL, 2017
Fuel cell	Smaller than 5 MW	NREL, 2017
Reciprocating engine	5 kW to 10.5 MW	Knowles, 2011
Stirling engine	1 kW to 50 kW	Knowles, 2011
Micro turbine	30 kW to 200 kW	Boukhanouf, 2011

engine, and the power produced is the same as the gasification process. Moreover, instead of using water, ORC uses a liquid organic chemical as the working fluid, and it is favourable in terms of thermodynamic principles, since it requires lower heat to evaporate.

Even though the utilisation of CHP is urgently needed, there are several constraints that permit this system from being installed in industry or for private usage. One of the limitations is the economic and technical uncertainty. Therefore, further research needs to be performed regarding technical issues, and comprehensive risk consideration should be taken into account to ensure the safety, reliability, and feasibility before CHP is selected as a primary energy producer in the future. One challenge is that it is difficult to find the end user for heat produced on a large scale (Dong et al., 2009). This is because household levels can only generate a small amount of electricity, whereas generation on large scales usually occurs at the industrial facilities equipped with CHP technology.

Fuel cell technology

A fuel cell is a system that converts the chemical energy of gas into electrical energy and heat without the combustion process as an intermediate step. This technology uses H_2 or H_2 -rich fuels and O_2 from air to produce electricity and heat (Giorgi & Leccess, 2013). The first principle of a fuel cell was discovered by a scientist in 1939 (Akinyele et al., 2020), while the first commercial use of a fuel cell was done with Project Gemini, developed through the collaboration of NASA and a chemist (Giorgi & Leccess, 2013). In the early stage, the main function of a fuel cell was to produce electricity and water. However, in recent years, as technologies have developed, the application of fuel cells has broadened. For example, besides producing electricity, this system is also involved in transportation. To date, this technology has gained interest due to its potential to effectively produce clean energy as an alternative for non-renewable energy, as well as its potential to mitigate the emission of CO into the atmosphere (Akinyele et al., 2020).

A fuel cell is a device that offers continuous conversion of chemical energy into electrical energy. The physical structure of this device consists of four main components: the cathode, anode, electrical circuit (Akinyele et al., 2020), and electrolyte layer, which is in contact with a porous

anode and cathode (Giorgi & Leccess, 2013). In general, gaseous fuel is fed on the negative side (anode) and oxygen from air is supplied through the positive side (cathode) (Giorgi & Leccess, 2013). At the anode, hydrogen is oxidised, forming an electron and hydrogen ion, while at the same time, oxygen at the cathode is reduced to its oxide species. The reaction between these two components forms water. Meanwhile, the electron is transported through the external circuit to deliver the power circuit (Mekhilef et al., 2011). The principle of a fuel cell is similar to a typical battery (Ellamla et al., 2015); however, unlike a typical battery, this fuel cell will continue to produce energy as long as the reactants are continuously supplied from its external source. Meanwhile, the energy produced in a typical battery is limited since the reactants are stored in the battery.

A fuel cell can be classified into several categories, according to the type of fuels, the operating temperature, the efficiency, their application, and the type of electrolyte used (Ellamla et al., 2015; Alias et al., 2020). The classification of fuel cells includes alkaline fuel cells (AFCs), polymer electrolyte membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), direct methanol fuel cells (DMFCs), and solid oxide fuel cells (SOFCs). Most of these technologies have been commercialised. Table 5 shows the different types of fuel cells and their characteristics. There are several advantages of fuel cells in electricity generation, such as their low maintenance, high electricity conversion (Akinyele et al., 2020), produce less waste and fuel flexibility. Fuel flexibility means that there are many types of fuel can be used in this system depending on its type, whether natural gas, hydrogen, biogas, and others (Giorgi & Leccess, 2013). Therefore, there will be wider applications of fuel cells in many sectors in the future.

POTENTIAL OF BIOGAS FOR THE GENERATION OF ELECTRICITY

Malaysia is a developing country that has managed to change the direction of its own economy from a traditional to a modern path. This is driven by rapid development across the nation. In terms of energy generation, the focus is now centred around a secure energy supply. However, the current trend shows that the existing non-renewable energy source is moving to the limit. Due to

Table 5. Types of fuel cells and their characteristics

Fuel cells	AFCs	PEMFCs	DMFCs	PAFCs	MCFCs	SOFCs	References
Operating temperature, °C	<100	60-120	60-120	160-220	600-800	800-1000	Giorgo & Leccese 2013
Electrolyte	KOH	Thin, permeable polymeric membrane	Polymer membrane	H ₃ PO ₄	Molten carbonate salt	Zirconium oxide	Akinyele et al., 2020
CHP efficiency	>80%	87-90%	80%	85-90%	85%	90%	Ellamla et al., 2015 Mehilef et al., 2011
Application	Military space	Backup power portable power small, distributed generation transportation	Replace batteries in mobiles	Distributed generation	Electric utility large, distributed generation	Auxiliary power electric utility large, distributed generation	Mehilef et al., 2011

this concern, the present power system starts to transform towards renewable energy sources.

Sustainable development is a process of developing something to meet the current need, without compromising the ability of future generations to meet their needs. At the moment, many countries in the world continue to develop their economy using unsustainable sources, such as the use of fossil fuels to generate energy. This is concerning, since these resources are depleting each day. Due to this, awareness has increased, and people around the world have begun to use renewable resources and to conserve resources, such as the use of biogas to generate energy. This gas is generated through anaerobic digestion of the substrates that mostly come from waste. The utilisation of waste will mitigate many environmental problems that arise, such as air pollution, water pollution, and earth pollution.

CONCLUSIONS

In summary, biogas production as an alternative to fossil fuels has great potential in the future. This opportunity becomes more crucial when environmental problems are taken into consideration. Moreover, this is even more significant since the electricity generated using biogas might help in the development of all countries in the world. To achieve greater production of biogas and high efficacy in its conversion to electricity, allowing for biogas to become one of the primary energy producers in the future, the challenges that may arise should be solved. It would also be a great alternative renewable energy and could reduce the dependence on fossil fuels.

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