



Biogas Production from Organic Waste: Recent Progress and Perspectives

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Abstract

Anaerobic digestion (AD) from organic waste has gained worldwide attention in reducing greenhouse gas emissions, lowering fossil fuel combustion, and facilitating a sustainable renewable energy supply. Biogas mainly consists of methane (CH₄) (50–75%), carbon dioxide (CO₂) (25–50%), hydrogen sulphides (H₂S), hydrogen (H₂), ammonia (NH₃) (1–2%) and traces of other gases such as oxygen (O₂) and nitrogen (N₂). Methane can replace fossil fuels in various applications such as heat and power generation and the transportation sector. The degradation of organic waste through an AD process offers many advantages, such as the decrease of pathogens and prevention of odour release. The digestate from anaerobic fermentation is a valuable fertilizer, however, the amount of organic materials currently available for biogas production is still limited. New substrates, as well as more effective conversion technologies, are needed to grow this industry globally. This paper reviewed the latest trends and progress in biogas production technologies including potential feedstock. Recycling of waste has recently become an important topic and has been explored in this paper.

Keywords Biogas · Anaerobic digestion · Conversion technologies · Recycling of waste

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List of Symbols

CO ₂	Carbon dioxide
CH ₄	Methane
CO ₂ e	Carbon dioxide-equivalents
AD	Anaerobic digestion
GHG	Greenhouse gases
NH ₃	Ammonia
H ₂ S	Sulphide
EJ/year	Exajoule/year
TWh	Terawatt hours
TS	Total solids
VS	Volatile solids
VFA	Volatile fatty acids
BMP	Biochemical methane potential
C/N	The carbon-to-nitrogen ratio
DM	Dry matter
ODM	Organic dry matter
COD	Chemical oxygen demand
HRT	Hydraulic retention time
OLR	Organic loading rate

Introduction

The widespread use of fossil fuels is responsible for the long-term environmental risks such as global warming. The key contributor to global warming is the emission of carbon dioxide (CO₂) that comes from many combustion sources. A recently published report by the European Environment Agency shows the extreme weather events related to global warming cost 400 billion Euros between 1980 and 2013 [1]. In addition, methane (CH₄) is 21 more times effective than CO₂ in trapping heat in the atmosphere [2]. CH₄ naturally exists in the atmosphere, however, its concentration is rapidly growing from the pre-industrial evaluation era, between the 1750s to 1990s due to human activities. The concentration has been increased 162% during these 250 [2]. Sources of CH₄ emissions include petroleum systems, agricultural and animal farms, landfills, mining, wastewater treatment, and certain industrial processes. According to World Resources Institute (CAIT data

in 2014), Table 1 shows the seven countries as top contributors to CH₄ emissions in carbon dioxide-equivalents (CO₂e) in 2014 with the three largest producers being China, the US, and India [3]. Overall, these seven countries were responsible for more than half of global CH₄ emissions in 2014.

Globally, non-CO₂ emissions from different resources increased approximately 10% from 1990 to 2005. The growth rate is projected to rise to around 43% between 2005 and 2030. Emission of CH₄ is expected to increase 26% during this time as shown in Fig. 1 [4].

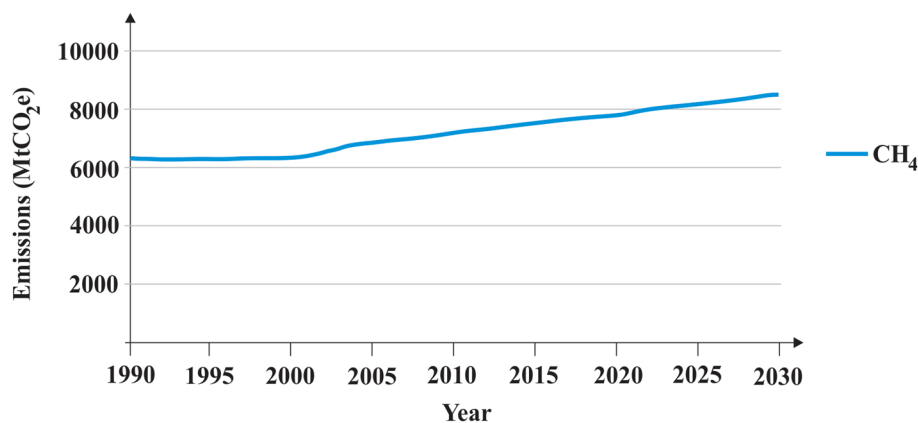
CH₄ emission sources can show variation from one area to another depending on climate, agricultural activities, waste management policies, manner industry and capability of CH₄ capture facilities. Environmental factors such as temperature and humidity have a significant influence on the anaerobic biological degradation of organic waste, which is known as an anaerobic digestion (AD) process [5]. This biological treatment process creates gases called biogas which includes CH₄ that is typically emitted into the atmosphere. Capturing CH₄ from these sources contributes positively to decrease uncontrolled CH₄ emissions and utilizes captured CH₄ as a renewable energy source. Biogas can be produced from different types of organic biomass under the absence of oxygen. CH₄ has been heavily used to produce power, heat and transportation fuel as a form of natural gas over the last century. Extensive use of CH₄ has drawn attention to maximizing the capture and use of biogas from biological degradation of organic waste which is material that is biodegradable and comes from either a plant or an animal and is able to be putrescible. Biogas plants have been designed according to biological degradation processes that can be fully controlled and optimized to produce renewable, sustainable biofuel.

The system can be defined as a net zero waste process due to creating energy from biogas and utilizing digested material (digestate) as an organic fertilizer. In addition, the AD system releases equal or less CO₂ to the atmosphere

Table 1 First seven top countries for methane-emitting in 2014 [3]

Countries	Total CO ₂ (including land-use change and forestry): 2014 (MtCO ₂ e)	Total CH ₄ (including land-use change and forestry): 2014 (MtCO ₂ e)	% of world total for CH ₄
World	48,892.37	7526.83	100
China	11,600.63	934.47	12.42
US	6319.02	666.86	8.86
India	3202.31	611.14	8.12
Russian Federation	2030.14	532.2	7.07
EU-28	3624.82	418.12	5.56
Brazil	1357.18	349.29	4.64
Indonesia	2471.64	303.11	4.03
Total for top seven countries	28,134.1	3815.19	50.69

Fig. 1 Global CH₄ emissions projected between 1990 and 2030 (MtCO₂e) (adopted from [4])



than biomass does due to fertilizer recovered and land applied, which contains carbon. Therefore, it has a positive impact in reducing global warming [5].

AD has been used for the treatment of animal manure and sewage sludge during its early age. Due to environmental concerns associated with other types of organic waste and the need to come up with more sustainable/green waste management strategies, organic waste from industrial and municipal sectors has been utilized as AD substrates since the 1970s. Moreover, advanced process control techniques and high rate reactor design options have made the wider adaptation of AD possible [6].

In the view of an increasing global energy demand and environmental awareness, biogas has engaged much more researchers' attention in the last 10 years. Because of this attention, journal publications published in this field have increased over the last 10 years. The Science Direct demonstrates that the number of published papers per year with “biogas” and “anaerobic digestion” as research topics was only 62 in 2000. In 2005, there were 114 published papers and publication rate started to increase exponentially. At the end of 2017, the cumulative number of papers published reached 1222 which included 112 review papers (Fig. 2) [7].

The aim of this review paper is to provide a comprehensive analysis and overview of the AD process related to its process mechanism, the effect of this mechanism and the efficiency of overall methane production. With the recent developments about the AD process and suggestions from academic researchers, this review paper investigated available data in the literature about substrates types, the production rates, and its yield to increase energy recovery. The innovation technologies are emphasized with their pros and cons for each section. This paper is organized as follows; “Biogas Status Around the World, Policies and Regulations” section gives information about the recent status of biogas

production and regulations all around the world. Biogas production, substrate types and characterizations are explained in “Formation of Biogas”, “Substrate for Biogas Production” and “Analysis and Characterization of Biogas Substrates and Process Parameters” sections, respectively. In the last section, the conclusion and suggestions for future research are covered.

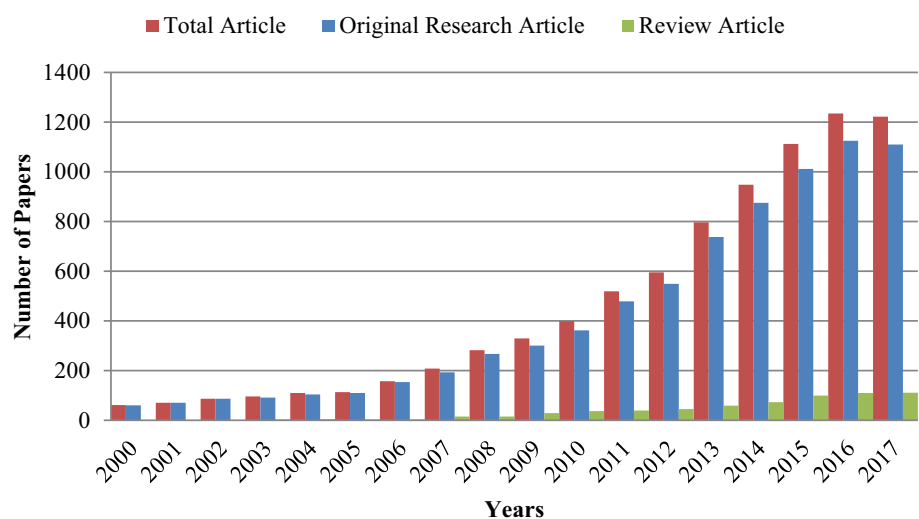
Biogas Status Around the World, Policies and Regulations

Historical Development

In 1891, the first document about AD was published in France. In 1895, the first biogas plant was built to treat municipal waste in England and the production of biogas was utilized to produce light and heat [8]. In 1936, Buswell and Hatfield [9] published a detailed report about AD in the US. Commercial applications of biogas plants appeared during the middle of the twentieth century. Their substrates generally had high organic loading rates (OLRs) digesting waste streams such as brewery and creamery wastewater [6]. Nowadays, AD is a well-established approach to treat wastewater and capture CH_4 . Its substrates are now municipal solid waste, different industrial waste, energy crops and more recently, aquatic biomass [10].

Biogas production has been used for small-scale applications in farms and households for years. After the requirement of sewage sludge stabilization, biogas production became a standard method for treatment of sludge for medium to large-scale treatment plans since the 1930s. With increasing efficiency of biogas production, biogas plants have increased to a more industrial scale over the last few decades, especially in Europe. At the beginning of the twenty-first century, it was recognized that biogas can play a

Fig. 2 Number of papers published with the topics of “biogas” or “anaerobic digestion” in the Science Direct [7]



key role to solve many problems simultaneously. Capturing CH_4 in biogas can provide reductions in the emissions of greenhouse gases (GHGs), production of renewable energy and management of waste disposal. Using biogas disposal as an organic fertilizer closes the life cycle. A study investigated biogas production from residual grass with a territorial approach and their results indicated that biogas production is an opportunity as a sustainable energy source opportunity if low distances (< 30 km) and a large availability of feedstock are available [11]. Countries set targets for the use of renewable energy and the reduction of GHG emissions. The production of energy from conventional solid biomass sources such as wood and hydroelectricity still has a higher percentage than other renewable energy sources globally. In developed countries, more recent technologies have been used to produce renewable energy such as industrial-scale biogas plants. However, this trend has not changed in developing countries. While reported biogas production was only 2% in the world as shown in Fig. 3a, it reached 7% in EU in 2013 as shown in Fig. 3b [12].

All of these facts have supported the fast growth in the biogas sector since 1990. Figure 4 shows the global trend for new renewable energy investments in biomass and waste to energy between 2004 and 2015 [13]. The trend shows a continual increase from 2004 to 2008 where it remains relatively constant. After 2011, fewer financial investments continued to be made. While the growth rate was -2% between 2004 and 2015, 6 billion dollars were invested in the biomass and waste to energy sector in 2015. Biomass and waste to energy investment decreased between 2011 and 2015 because the sector has become more mature especially in developed countries such as Germany, England, and Denmark. However, the investment continues to gradually increase in developing countries due to their economic situations.

To produce biogas, consortia of bacteria digest biomass under oxygen-free conditions. The two main products of this process are CH_4 and CO_2 . The CH_4 component of biogas is between 50 and 75% while the CO_2 component is between 25 and 50%. This fluctuation depends on substrate type due to its chemical components and biodegradability. The remaining components are water vapour (H_2O), sulphur (S_2), hydrogen sulphide (H_2S), and ammonia (NH_3). During the process of upgrading biogas to bio-methane, the purity of CH_4 reaches approximately 96–98%. This upgraded biogas shows similar properties to natural gas [14].

Using food based substrates to produce energy still has conflicting viewpoints around the world. However, using waste and inedible energy crops as a substrate is a promising alternative to produce energy via AD. Globally, unused organic waste and uncultivated areas that could be used for energy crops are a significant potential for AD substrate. In some scenarios, development of renewable energy estimation is between 173 and 400 Exajoule/year (EJ/year) in

2050 [15]. Generating energy from the waste and traditional energy crops were evaluated and the potential was projected to be between 62 and 325 EJ/year within different estimations for 2050 [16]. These estimations demonstrate that generating energy from biogas can make a valuable impact on sustainable energy source in the form of electricity, heat, and vehicle fuel.

To meet the National Renewable Energy Action Plan (NREAP) expectations in the EU for 2020, the renewable energy sector has to grow 4% each year until 2020. In the 2015 Paris Agreement, the EU's target for 2050 is an 85–90% reduction in GHG emissions from the amounts produced in 1990 [17]. According to the Biogas Report 2014 [18] published by the European Biogas Association, Fig. 5 shows electricity production from biogas in some EU countries in 2013. In the EU, the electricity production from biogas must be increased between 2013 and 2020 from 46.8 to 63.3 terawatt hours (TWh) to meet their NREAP target. Some EU countries such as Germany and Italy are anticipated to achieve their target due to their number of operating biogas plants; however, other countries need to develop policies and provide financial investment to develop and operate more biogas plants.

In the North America, animal manure has been stabilized using AD until the middle of 1970s [5]. With the further development of AD, the number of biogas plants in the US has increased. The current number of operating AD plants has reached over 2100, however, it is still far below their ideal potential [19]. Electricity generated from biogas in the US was approximately 981 GWh in 2015 [20]. Figure 6 shows the utilization of biogas produced from livestock farms in 2015 in the US [21].

In Japan, AD has an increasing trend over the last decade due to the advantageous use of AD to manage and treat waste. Japan is currently the only country using thermophilic AD techniques in the region [5]. In 2006, 200 ML (fuel oil equivalent) biogas was produced. Biogas production from sewage sludge has been increased in several cities in Japan such as Kobe (capacity of 800,000 m^3/year), Nagaoka (capacity of 600,000 m^3/year), and Kanazawa (capacity of 280,000 m^3/year) [22].

AD technology has been gaining more attention and is more suitable for developing countries because of their higher energy cost than developed countries. China and India currently have the largest number of biogas plants in operation with 42.6 million and 4.7 million, respectively as shown in Fig. 7a [23]. In China, biogas production as a renewable energy source has been promoted due to a renewable energy tariff policy. Unfortunately, some factors of this policy block the rapid development stage such as a feed-in tariff, grid connection expenses, and tariff surcharge subsidies [24]. Feed-in tariffs are relatively high for a biogas power plant. As a result, the biogas power plants are not able to compete with

Fig. 3 Energy source at the **a** global and **b** EU-28 level in 2013 (adopted from [12])

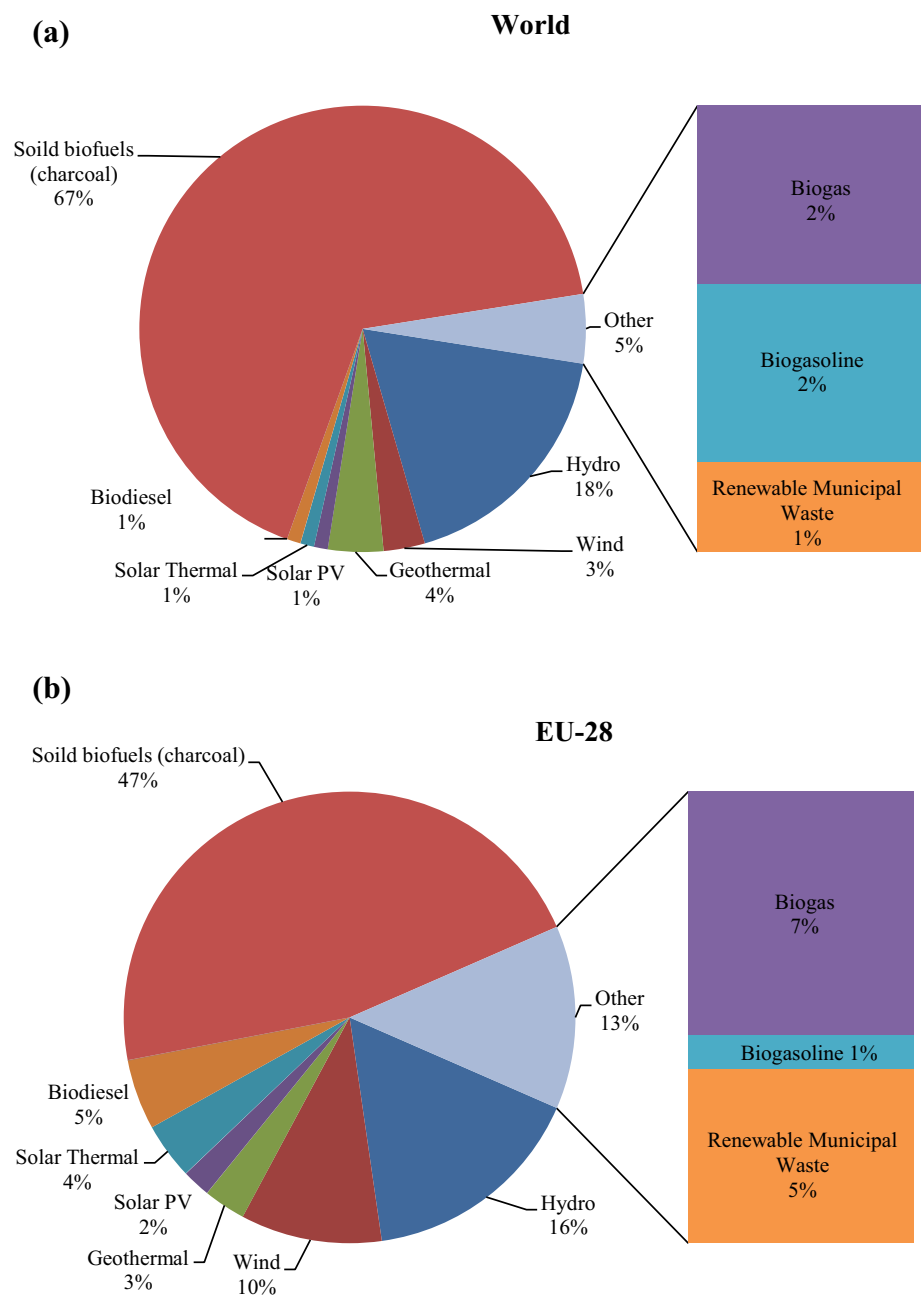


Fig. 4 New global renewable energy investments in biomass and waste to energy (adopted from [13])

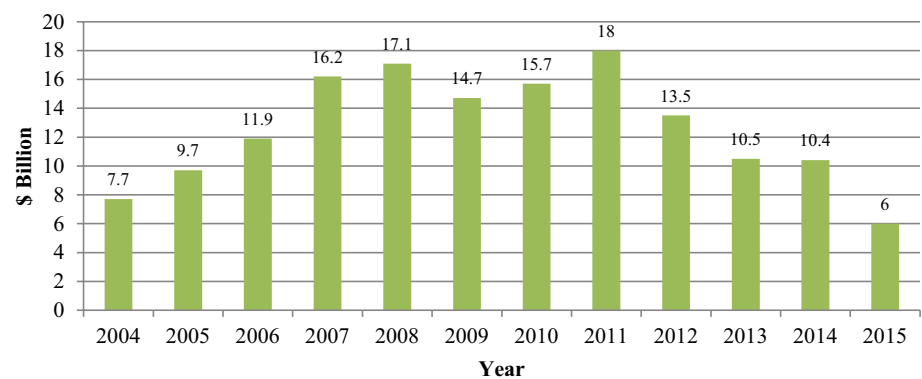


Fig. 5 Electricity production from biogas in EU in 2013 (adopted from [18])

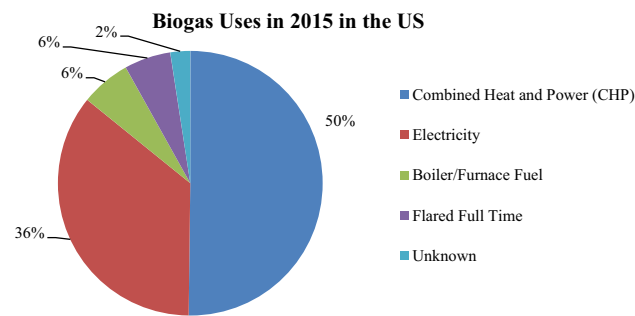
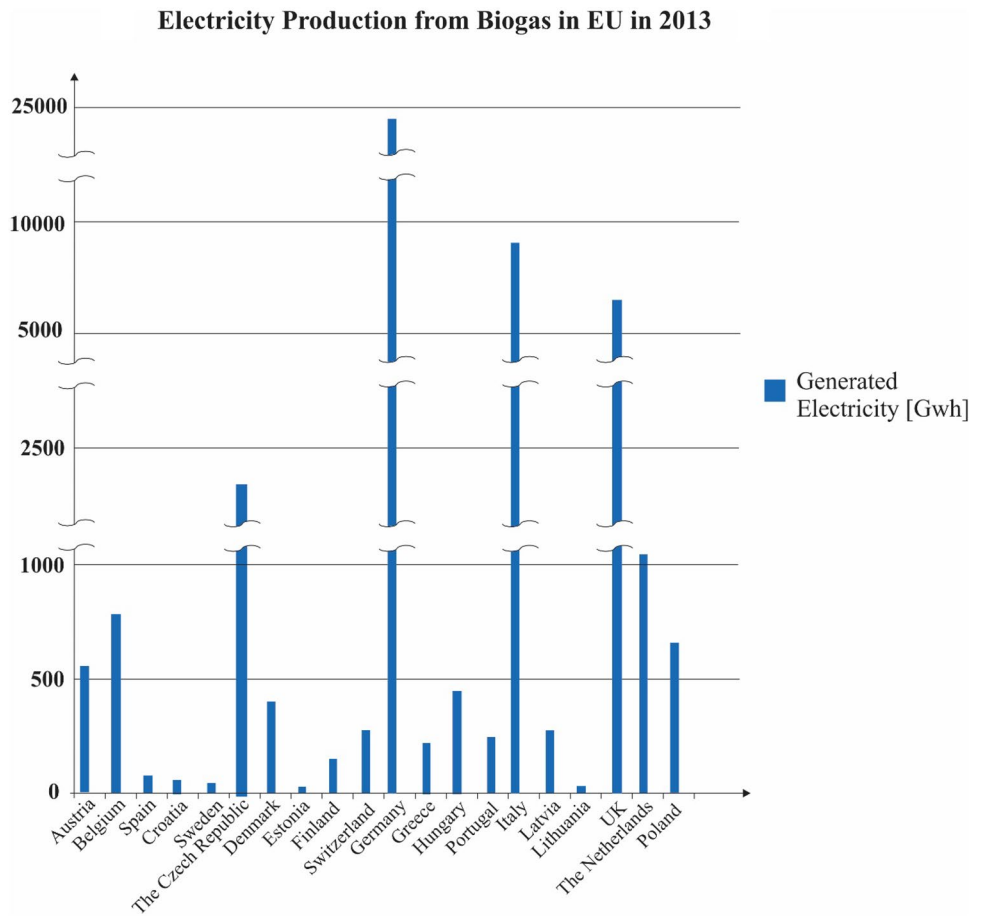
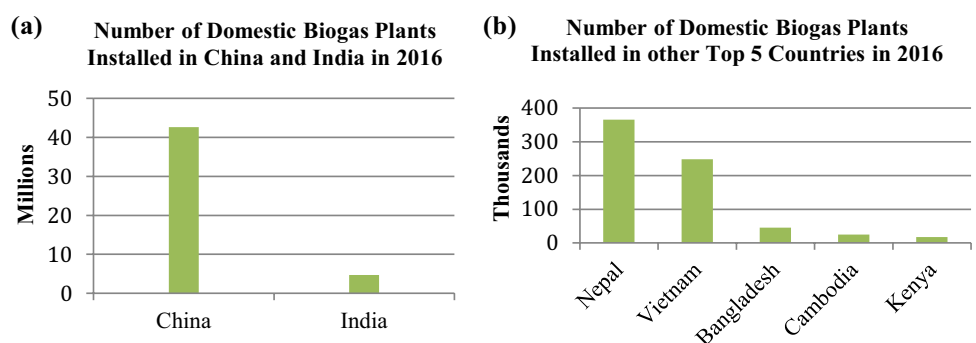


Fig. 6 Produced biogas utilization pathways in 2015 in the US [21]

conventional energy companies in the energy sector. Additionally, the standard subsidy of grid connection expenses is low which makes the investment of a grid connection unattractive [24]. Moreover, some feedstock types have a unified feed-in tariff adversely affects biogas production regionally.

Other Asian countries such as Nepal, Vietnam, Bangladesh, Cambodia, and Kenya have an increasing trend for domestic biogas plants. The number of biogas plants in these countries are between 360 and 15,000 as shown in Fig. 7b [23]. In India, over 1.2 million households use small scale AD to meet their cooking energy demands and 100,000 family size AD systems

Fig. 7 Number of domestic biogas plants installed in China and India and the other top five countries in Asia (adopted from [23])



have been installed between 2016 and 2017 in India [25]. More than 35,000 biogas plants have been built with support from India's government [25]. Asia has made larger investments in AD technologies than any other regions in 2016. In Africa, 68,000 biogas plant started operation in 2016 that were related to the African Biogas Partnership Program [23]. Over 700,000 biogas plants have been installed in developing countries as of 2015 [23].

Regulations

Pathogenic bacteria contained in digestate may easily spread into the environment and biogas may also be leaked from plants unexpectedly. These kinds of risks have been heavily discussed due to a huge impact on the health of both people and animals, and also environmental concerns. A study has reported that the number of pathogens in the waste stream are decreased during the digestion process [26]. Without any further treatment, digestion residue could be used as an organic fertilizer, however, this might contain highly undigested substrate (i.e. wastewater sludge, manure, food waste, farm residues). Furthermore, if there is a concern about digestion residual that poses a health risk, an additional treatment has to be applied before being released to the environment. Because of all these risks, land application of AD digestate as fertilizer has to be regulated. Furthermore, policy makers often support renewable energy production with regulations due to energy security and independence. If any crisis occurred, a country could meet a part of their energy demands from the energy produced within the country.

In the EU, usage, treatment, and disposal are regulated under the Regulation 1069/2009 [27] if AD feedstock is based on organic waste and animal by-products. European Animal By-products Regulation (ABPR) was upgraded in Regulation 2002/1774/EC [28]. According to ABPR, some feedstock is suitable for AD but not suitable for combustion. Therefore, biological safety monitoring is necessary for AD plants if they use these substrates. Special procedures are required for handling and further usage of this material. These mandatory processes are defined in the EU Waste Framework Directive [29] and Regulation 1069/2009. Figure 8 shows the timeline of regulations related to AD in the EU. According to Regulation 1069/2009, category 3 materials, which include food waste, kitchen and canteen waste, and content of fat separators, must be treated at 70 °C for an hour after the AD process.

In some European countries, there are additional regulations for AD plants. For example, if grass silage is used as a co-substrate with municipal waste, the entire digestate is considered a waste and therefore waste regulations are applied. In Denmark, if feedstock contains 25% organic waste, they accept digestate as animal manure and apply manure and slurry regulations. If it is less than this ratio, they accept it as sewage sludge and digestate can be used as fertilizer [31].

In the US, there are no national regulations related to agriculture waste and animal manure, unlike the EU. For GHG emissions, there are also no federal targets in the US; however, there are some regulations at the state level. 37 States have passed the Renewable Portfolio Standards regulation to clarify their target for renewable energy production [30]. The relatively low price of natural gas in the US may be the main motivation not to legislate at the federal level. However, the Renewable Fuel Pathways II Final Report [32] described that renewable electricity produced from biogas can be used in electric vehicles which promotes the development of biogas plants located in the US in the near future [30].

In China, the federal government supports improvement in renewable energy usage and development. In 2006, the Renewable Energy Law was legislated to meet their target for GHG emissions of 40–45% reductions by 2020 [33]. The use and improvement of renewable energy have been supported under this law. In 2009, the government modified some parts of the law including a mandatory connection and purchase policy. Specific targets were described for each renewable energy source in the China 12th Five Year Plan for Renewable Energy from 2011 to 2015 [24]. Generating energy from biomass improved significantly under these regulations and biogas power production planned to reach 12 TWh over these 5 years [24].

Formation of Biogas

AD is the biological decomposition of organic substrate in an oxygen-free environment. During this process, biogas as an energy carrier, and digestate are produced. Biogas is mainly composed of methane (CH₄) and carbon dioxide (CO₂). Chemical bound energy in the feedstock is almost constant throughout an AD process. It only changes in the form of CH₄ [34].

The biological process is very complex and is multiphase. In the past decade, process control devices and analysis

Fig. 8 EU policy initiatives related to biogas plant (adopted from [30])



tools have been developed. These developments have made a significant improvement in AD processes. Thousands of different kinds of bacteria and several biological steps are included. Some of these periods are extremely complex, however, all these steps occur simultaneously. Due to these complex steps, effective monitoring and control systems are essential to reach a high level of CH_4 yield during the AD process in biogas plants. The purpose of the control system is to optimize the complete biogas production process and to give early warning to prevent failure of the entire process. Online monitoring can be produced with multivariate data analysis and process analytical devices such as fibre optics and spectrophotometers. Process analytical chemistry allows the digital measurement of process parameters such as total solids (TSs), volatile solids (VSs), volatile fatty acids (VFA), and pH [35]. The parameters continuously indicate the stage of the process and when these parameters reach unexpected values, the system indicates that the process must be intervened. With development of control systems and analysis, biogas plants can operate smoothly despite of these extremely complex steps.

Biochemical Reactions

In AD, biochemical steps are linked to each other. After some bacteria use the substrate as a food source, they produce some by-products, which are a food source for the other bacteria. The process can be divided into three main phases which are namely hydrolysis, acidification, and methanogenesis as shown in Fig. 9 [36]. These process steps work simultaneously in the same digester. Significant gas production occurs during the methanogenic phase.

Hydrolysis Phase

The hydrolysis phase is the first step for AD. Water-soluble materials are decomposed into small compounds. Long chain carbohydrates, proteins, and fats are converted into short chain sugars, amino acids and fatty acids, respectively. The hydrolysis phase occurs in a few hours if the substrate is composed of carbohydrates, and in a few days if the substrate is composed of protein and lipids. However, if substrate compounds include lignin and lignocellulose, the process can take several days and complete digestion cannot be completed [37].

Acidification Phase

Acid production is the second step in the AD process. The microorganisms produce acetic acid, H_2 , and CO_2 . In this step, microorganisms cultivate under acid conditions. They

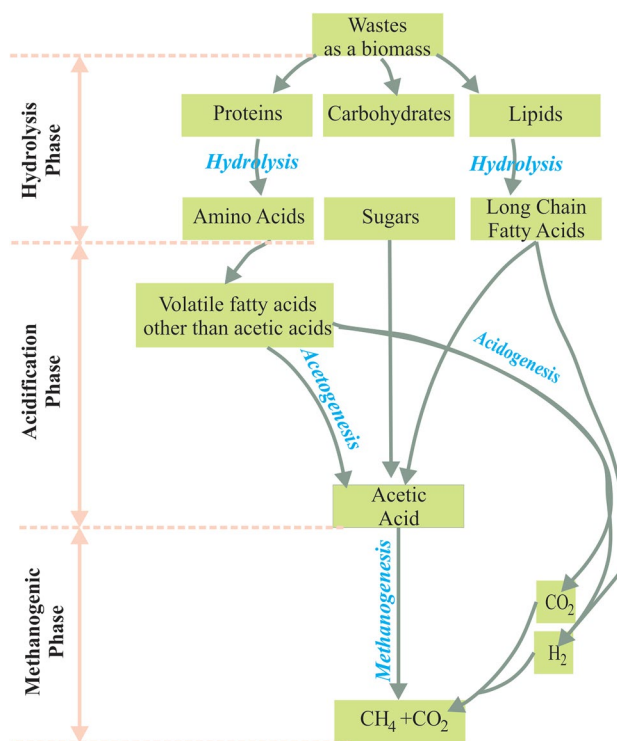


Fig. 9 Proposed metabolic pathway for methane production from organic waste with anaerobic digestion (adopted from [36])

use the oxygen dissolved in the solution or oxygen from other molecules to produce acetic acid. At the end of this stage, they produce alcohols, organic acid, amino acid, CO_2 , H_2S and traces of methane [38]. The acidification phase can be divided into two steps, which are acidogenesis and acetogenesis.

Acidogenesis Acidogenic bacteria transform the products of hydrolysis into a food source for methanogenic bacteria during acidogenesis. Most of the microorganisms during the AD process are transformed in this stage. Short chain sugars, amino acids and fatty acids are biologically changed to, alcohols, ammonia, CO_2 , and H_2 , and acids such as acetic, propionic acid, and lactic acid [36]. The products are related to the substrate types, operating conditions and microorganism types. In this stage, the amount of CO_2 and H_2 in the products are approximately 70% and acids and alcohols are approximately 30% [34].

Acetogenesis Acetogenic bacteria convert the product of acidogenesis into a methanogenic substrate. Acetate, H_2 , and CO_2 are products of acetogenic bacteria produced with the oxidation of VFAs and alcohols. When the partial pressure of hydrogen is increased due to acetogenic bacteria's products, the acetogenic bacteria are inhibited [34].

Hydrogen is transformed into methane by methanogenic bacteria. These two species work simultaneously.

Methanogenic Phase

Most components of biogas are produced during the methanogenic phase. Methanogenic bacteria generate 70% of the methane from acetate and the rest of it from the transformation of H_2 and CO_2 [34].

During the AD process, methanogenesis is the most critical phase because methanogenic bacteria are the most sensitive group. Operating conditions have significant effects on methanogenic bacteria such as substrate type, temperature, pH and feeding rate. Overloading the digester, temperature fluctuation more than 3 °C and large amounts of oxygen present can terminate the AD process due to methanogenic bacteria sensitivity [34].

Overall, different types of bacteria work in the same digester reactor under a single condition. The last two steps require different environmental conditions, have specific substrate needs, and the last step is slower than the previous steps. In conventional (single-stage) AD, process parameters are adjusted according to the last step due to the sensitivity of methanogenic bacteria.

Substrate for Biogas Production

In general, several types of biomass can be used as a substrate to produce biogas if their main components are carbohydrates, proteins and fats. Selected substrates should have certain properties such as being suitable for the fermentation process, contain a high nutritional value, and the digestate should be free of pathogens and heavy metals for land applications such as fertilizer.

The substrates used for biogas production can be divided into three main groups which are agricultural wastes, municipal waste, and industrial waste. In addition, energy crops can be used as a substrate which is discussed further in agricultural waste. Lastly, aquatic biomass is a promising substrate to generate biogas and its properties are explained in the last section.

Agricultural Waste

Agricultural waste refers to waste produced from various agricultural activities. In recent years, this waste has become a concern due to environmental problems and contribution of GHG emissions. The agricultural industry generates around 90 million tons of waste each year in EU [39]. In addition, an estimation shows that 30% of food product all

over the world end up as waste due to food disposal and waste directly from the agricultural industry [39]. 50–110 m³ of CO_2 and 90–140 m³ of CH_4 are released into the atmosphere from 1 ton of organic solid waste due to degradation [40].

Agricultural waste is a commonly available substrate for use as a primary source to produce biogas. Therefore, effective use of agricultural waste has a positive impact on countries' economy and waste disposal problem. These substrates include animal manures and slurries, crop waste and agricultural by-products. When animal waste is not used for AD, they have large impact on wetland habitats and lead to polluted drinking water sources. Crop residues such as stalk, straw, and bark, are utilized for energy production throughout the AD process. Crop residues are mainly combined of lignocellulosic mixtures which are cellulose, hemicellulose, and lignin. They are the main elements of the cell walls and are difficult to digest because of their high lignocellulosic content.

Energy crops have gained significant attention in some countries such as Germany and Austria since 1990. Many studies have concluded that energy crops are suitable to produce biogas via AD [34, 41–44]. Murphy et al. [10] comprehensively reviewed energy crops and their potential methane yield as shown in Table 2. There are some preparation steps, which include harvesting, processing, and storage in order to use energy crops for AD. Energy crops can be used after harvesting or stored for year-long availability. Murphy et al. [10] reported that matured energy crops are useful as feedstock because cellulosic structures increase with maturity and an affect methane yields negatively. Furthermore, well matured crops have longer storage life. However, Franco et al. [45]. studied the storage of cattle manure and their results indicated that methane potential decreased by 37% after 120 days of storage.

The harvesting time of feedstock has an impact on the methane yield. The biochemical methane potential (BMP) test shows that the grass should be cut 3–4 days after dairy cattle feeding [46]. The percentage of cellulose, hemicellulose, and lignin in feedstock increases with maturity while protein, lipid, and sugars decrease. During the AD process, substrates which contain high lignocellulosic material are difficult to digest. To reach high methane yield, feedstock has a low lignin content and high carbohydrates, soluble cell components [46]. Frigon et al. [47] studied switchgrass, and their results indicated that the fresh switchgrass harvested in the summer had a higher methane yield than winter harvested switchgrass due to its lignin concentration. The methane yield of summer harvested switchgrass was 0.298 m³/kg VS while the methane yield of winter harvested switchgrass was 0.140 m³/kg VS. This is due to the lignin percentage in the summer and winter harvest being 28.1% and 22.3%

Table 2 Some common agricultural waste and energy crops and their methane yields (adopted from [6, 10])

Agricultural waste and energy crops	Methane yield (m ³ /kg VS)
Grass	0.298–0.467
Clover grass	0.290–0.390
Hemp	0.355–0.409
Sunflower	0.154–0.400
Oilseed rape	0.240–0.340
Potatoes	0.275–0.400
Sugar beet	0.236–0.381
Fodder beet	0.420–0.500
Barley	0.353–0.658
Triticale	0.337–0.555
Alfalfa	0.340–0.500
Ryegrass	0.390–0.410
Nettle	0.120–0.420
Straw	0.242–0.324
Leaves	0.417–0.453
Cattle manure	0.200
Pig manure	0.300
Poultry manure	0.300

of the TS content, respectively [47]. Table 3 shows recent agricultural waste studies and their methane yield.

Municipal Solid Wastes

Municipal solid wastes refer to organic household waste, and food residues. In the US, 30.1 million metric tons of municipal solid wastes were produced in 2014 [2]. Generally, these wastes come from end-users of products and have rich organic nutritional value. Therefore, they have great potential as an AD substrate and they should be collected separately. Thus, it improves full recycling process efficiency. Separately collected municipal wastes are usually used as a co-substrate with animal manure or slurry to increase methane yield.

Depending on a country's income, municipal solid waste is typically produced at a rate between 1.1 and 2.2 kg/person/day. Globally, approximately 1.3 billion tonnes of municipal solid waste is generated each year. Moreover, it is projected that this amount will rise to 2.2 billion tonnes each year by 2025 [59]. Municipal solid waste is generally disposed of either at a landfill, through composting, or open dumping. If the treatment is not appropriate, it may create water and soil pollution due to heavy metals contained in the leachate, air pollution owing to odour emissions, and biological degradation. Approximately 5% of total CO₂ emissions and 9% of CH₄ emissions are generated from municipal solid waste [59, 60]. Therefore, recycle and reuse concept may

Table 3 Some recent studies and their methane yield

Agricultural waste	Methane yield (m ³ /kg VS)	References
Switchgrass	0.140–0.298	[47]
Grass	0.190–0.198	[46]
Hay	0.236–0.281	[46]
Wheat straw	0.270–0.288	[48]
Peanut hull	0.112–0.182	[49]
Cauliflower stems	0.331	[50]
Beet leaves	0.231	[50]
Citrus waste	0.137	[51]
Yard waste	0.243	[52]
Exhausted fungal (<i>Trametes versicolor</i>)	0.281–0.595	[53]
<i>Spartina alterniflora</i>	0.177	[54]
Winter wheat	0.360	[55]
<i>Miscanthus lutarioriparius</i>	0.238	[56]
Maize	0.259	[57]
Cattle slurry	0.156–0.240	[58]

be a key solution to manage this waste problem. Municipal solid waste consists of 46% food scraps and garden waste, 17% paper, 10% plastic, and 27% other waste [59]. Moreover, the percentage of organic waste in the municipal waste is 50–70% for low-income countries and 20–40% for high-income countries [59]. Due to the combination of the waste, the carbon-to-nitrogen (C/N) ratio varies, such as food scraps and garden waste have a C/N ratio less than 20 and paper typically has a C/N ratio of more than 100 [61].

There are some challenges for using municipal solid waste for AD process including high solid content, large particle size, and heterogeneous mixture. Therefore, a co-digester is the best option for this waste. In literature, the waste is mixed with sewage sludge, manure, or wastewater. Table 4 shows some recent studies about municipal solid waste and their methane yield.

Industrial Waste

By processing different raw materials, various industries produce enormous amounts of by-products, residues, and waste that can be used for AD. In a biogas plant, this waste is used as methane boosters due to their rich organic contents. However, the major challenge is the unpredictable contents of this waste. Based on their production techniques, the waste's contents may include impurities, pathogens and heavy metals. These contents can break down biological consortia in the reactor and inhibit the AD process. Furthermore, there is an environmental pollution risk and health risk for people and animals when the digestate is utilized as fertilizer. As a result, many countries have implemented environmental legislation to limit the usage of waste. Industrial waste can

Table 4 Recent studies about municipal solid waste co-AD process and methane yield

Substrate types	Methane yield (m ³ /kg VS)	References
Municipal solid waste and activated sludge	0.340	[62]
Municipal solid waste and activated sludge	0.376	[63]
Municipal solid waste and sewage sludge	0.395	[64]
Hydromechanically separated municipal solid waste and sewage sludge	0.333	[65]
Municipal solid waste and activated sludge	0.287	[66]
Municipal solid waste and biogas plant inoculum (cow manure and food waste)	0.401	[67]
Municipal solid waste and pig manure	0.377	[68]
Municipal solid waste and cattle manure	0.443	[69]
Municipal solid waste and food waste	0.396	[70]
Municipal solid waste and agricultural waste (rice straw)	0.403	[69]
Municipal solid waste and wastewater (leachate)	0.232	[71]

be divided into two main groups, which are namely food industry wastes and other industrial waste such as pulp and paper industrial wastes, textile industrial waste, petrochemical refinery waste and oil cake (liquid biofuel production wastes).

Food Waste

The food industry is a large sector and covers fruits and vegetables, edible oil, dairy production, seafood, meat production, sugar, brewing and different beverages [72]. Their waste contents are rich in fats, proteins and carbohydrates, especially dairy production industries. As expected their production of waste is high and is also suitable for the generation of renewable energy via an AD process.

In the literature, food waste can be divided into three main sections as food waste referring waste from hotels, restaurants, canteens, and companies, kitchen waste referring to waste from domestic and commercial kitchens, and fruit and vegetable waste referring waste from markets and, fruit and vegetable distributors.

Food waste shows variations depending on the region and season. Zhang et al. [73] recently reviewed the food waste and they reported that food waste has 0.440–0.480 m³/kg VS methane yield. This waste has some benefits such as low cost for collection and transportation, high biodegradability and high methane yield [74]. However, a single food waste substrate system for an AD process might cause failure because of acid accumulation if the OLR is not fixed [75]. Vegetable fruit waste also has low biodegradability due to its high lignocellulosic content. Additionally, a recent study showed that NaCl inside this waste could play a key role for inhabitation of the reactor as acidogenesis and methanogenesis are inhibited via salinity inside food waste [76].

Fisgativa et al. [77] reported that pH, dry matter (DM), and VSs of food waste are 5.1, 88.2% DM, and 22.8%

weight/weight, respectively, based on 102 samples which are obtained from the literature. Moreover, the specifications of food waste show differentiation between summer and winter, long holidays, and regular working days, and regions [77, 78]. Therefore, additional food waste characterizations are required to fill in these gaps.

Fruit and vegetable waste has more biodegradability and higher methane yields than other agriculture products due to its lower lignin content. According to published reports, the biodegradability of fruit and vegetable waste is between 50 and 70% [79–81]. Beside high methane yields and biodegradability, the waste has low pH value such as 3.42 for orange peel [80], 3.88 for strawberry extrudate [82], and 3.53 for onion waste [83]. The low pH value may affect AD process because of acidification, therefore, the waste should be used with a co-substrate for AD. Table 5 shows some recent studies about food waste and their methane yield.

Other Industrial Waste

Pulp and paper production creates high volumes of waste. Pulp is produced from 40 to 45% of the input wood weight; therefore, the waste has a high chemical oxygen demand (COD) [85]. Their effluent leaves the process around 35 °C [72] which is more beneficial for the AD process. The waste from the pulp and paper industry has high lignin (5.68%), hemicellulose (6.53%) and cellulose (39.31%) content [86, 87]. Due to its contents, the industrial waste was not widely used for AD process because of requested long solid retention time required and its low degradation. Meyer and Edwards [88] reported that the waste requires a long retention time, which is between 30 and 60 days, and it has low biological degradation, which is around 30 and 50% of the organic matter. Using co-digestion technology, the waste has been widely used as a substrate. A recent study reported that pulp and paper industrial wastes were

Table 5 Types of food waste and their methane yield

Substrate types	Methane yield (m ³ /kg VS)	References
Food waste	0.440–0.480	[73]
Kitchen waste	0.700	[84]
Orange peel	0.230–0.332	[80]
Strawberry extrudate	0.285–0.339	[82]
Onion skin	0.400	[50]
Carrot petioles	0.309	[50]
Potato skin	0.267	[50]
Cucumber waste	0.143	[79]
Fluted pumpkin peel	0.161–0.164	[81]
Banana skin	0.277	[50]

used for AD as feedstock under different conditions and their methane yield was between 0.018 and 0.126 m³/kg VS [89]. To obtain a high methane yield, pre-treatment is necessary. Table 6 shows methane yields which were obtained from pulp and paper industrial waste.

The textile production process can be grouped into three steps which are washing, dyeing, and finishing. During all of these steps, water is used; thus, this industry creates a significant amount of wastewater. The wastewater includes fibers, dyes, and finishing products that contain various types of chemicals. Several studies reported that sequential anaerobic and aerobic treatment should be applied to the wastewater [93, 94]. A study reported that 0.200 to 0.400 m³/kg VS methane yield were obtained from textile wastewater [95]. Another study supported this result with reporting 0.227 m³/kg VS methane yield [96]. Lin et al. [97] recently figured out that methane yield from textile wastewater was 15.5 mmol/(L day).

Petrochemical refineries produce aldehydes, acids, alcohols, and esters which are suitable for AD. Chen et al. [72] reported that processing their waste with AD can lead to energy savings through the production of CH₄ by aerobic treatment. Haak et al. [98] studied oil refinery wastewater with an AD process by applying ozone pre-treatment. Their results indicated that the waste might use as a feedstock for biogas production, but it produced a low biogas yield of 35 mL after 45 days [98]. Another study showed that

diesel fuel and spent engine oil can be used for AD [99]. For 14 days experiment, 0.124 and 0.09 mL CH₄ was produced from diesel fuel and spent engine oil, respectively [99]. Moreover, Wang et al. [100] investigated microbiology morphology and their methane production rate was 0.6 L/(L day). However, most studies available in literature have investigated inhibitory behaviours of petrochemical refinery waste on the AD process. There are a few studies for the use of a co-digester with petrochemical refinery waste in the literature. Mehryar et al. [101] studied oil refinery wastewater and chicken manure as co-digestion and obtained 0.160 m³/kg VS. Additionally, different bioplastic wastes were recently studied as a substrate for co-digestion. The report showed that the methane yield was around 0.400 m³/kg VS [102]. The use of co-digestion has limited information in the literature, and therefore, it should be studied with different feedstocks.

The production process of liquid biofuel from energy crops produce high amounts of organic by-products, which have suitable properties for being feedstock for AD. Silage and sugar cane are used to produce bioethanol. Drogg et al. [103] published that with a dry grind bioethanol production process, 5.6 kg of stillage is generated to produce 1 L of bioethanol. According to this data, it can be calculated that 562.9 billion kg of stillage was produced to obtain bioethanol in 2016. The stillage has recently been used as animal feed using a drying process. If this stillage were used as an AD substrate, it would have captured 32.7 billion Nm³ of methane. Their by-products have high biological degradability and they are suitable for biogas production [104, 105]. Moreover, glycerol [106, 107] and wastewater [108] from biodiesel production are appropriate substrates for AD. Khuntia et al. stated that each litre of biodiesel production from *Pongamia pinnata* and *Jatropha curcas* (JC) produces 6.97 and 5.15 kg of waste, respectively [109]. Rapeseed oilcake used as a feedstock biogas production has a methane yield of 0.310 m³/kg VS [110]. Its methane yield is relatively high when compared with JC oil cake, which is around 0.250 m³/kg VS [111] and sunflower oil cake, which is 0.195 m³/kg VS [112]. Table 7 shows different types of oil cakes and their methane yield.

Table 6 Pulp and paper industrial waste and their methane yield

Substrate types	Methane yield (m ³ /kg VS)	References
Pulp and paper mill sludge	0.429	[90]
Pulp and paper industry biosludge (without–with pretreatment)	0.018–0.126	[89]
Pulp mill biosludge and monosodium glutamate waste liquor	0.245	[88]
Pulp and paper industry wastewater (without–with pretreatment)	0.078–0.138	[91]
Sedimented fiber originating from pulp and paper industry	0.201	[92]

Table 7 Types of oil cakes after biodiesel production and their methane yield

Substrate types	Methane yield (m ³ /kg VS)	ReferenceS
Rape oilcake	0.310	[110]
<i>Jatropha curcas</i> oil cake	0.250	[111]
Sunflower oil cake	0.195	[112]
Decanter oil cake and sewage sludge	0.330	[113]
<i>Eruca sativa</i> seed oil cake	0.212	[114]
Glycerol and cattle manure	0.734	[115]
Glycerol and swine manure	0.834	[116]
Wastewater from biodiesel plant	0.161	[117]

Aquatic Biomass

Aquatic biomass has gained attention as a third-generation feedstock during recent years. They can be used as a raw material for different industries, especially biofuel production that includes biogas [118, 119]. There are two groups of aquatic biomass. The first one is a macroalgae known as seaweed. Their contents include high-level sugars and carbohydrates. The second group are microalgae that are unicellular microscopic organisms. Green microalgae can be viewed as an appropriate substrate for biogas production. They have a high efficiency for photosynthesis and contain a rich lipid. The main drawback of microalgae is its low DM content [120]. Aquatic biomass has been heavily studied in academia for the last decade. Now, it has become a mature subject within the industry. There is solid proof that alternative biofuels sourced from seaweed were added in the EU target by the EU Environment Committee in 2015. The target is that 1.25% of the energy demand in the transportation sector will be produced from seaweed by 2020 [118]. Yue et al. [121] reported that adding goethite into an algal biomass anaerobic digester increased the methane yield by 24.1% due to influencing methanogenic microorganisms. Table 8 presents common microalgae and their methane yields.

Analysis and Characterization of Biogas Substrates and Process Parameters

Most of the organic substrates from different sources such as municipal solid waste, industrial by-products and agricultural waste can be used for AD. However, not all of them meet some expectations such as high methane yields and do not show inhibitory behaviours. The AD process can be inhibited by high OLR, macronutrients, micronutrients, high or low pH value, high temperature,

Table 8 Some microalgae species and their methane yields

Microalgae species	Methane yield (m ³ /kg VS)	References
<i>Arthrospira platensis</i>	0.293	[118]
<i>Chlamydomonas reinhardtii</i>	0.387	[118]
<i>Chlorella kessleri</i>	0.218	[118]
<i>Dunaliella</i>	0.420	[118]
<i>Dunaliella salina</i>	0.323	[118]
<i>Spirulina</i>	0.424	[118]
Green algae	0.310	[118]
<i>Chlorella</i> sp.	0.264	[48]
<i>Monoraphidium</i> sp.	0.264	[48]
<i>Chlorella vulgaris</i>	0.150–0.350	[122]
<i>Chlorella vulgaris</i> and cattle manure	0.431	[123]
<i>Isochrysis galbana</i>	0.338	[124]
<i>Selenastrum capricornutum</i>	0.209	[124]
<i>Scenedesmus</i> sp.	0.351	[124]
<i>Scenedesmus</i> residue after lipid extraction	0.100–0.150	[122]
<i>Chlorella</i> and waste activated sludge	0.253	[125]
<i>Micractinium</i> sp. and waste activated sludge	0.236	[125]
<i>Isochrysis galbana</i> and sewage sludge	0.356	[126]
<i>C. sorokiniana</i>	0.322	[127]
Water hyacinth and cow manure	0.156	[128]

un-dissociated organic acids, competitive microbes, and substrate-derived toxic substances [129]. These inhibitory behaviours cause the entire process failure and the practical difficulties can be faced in the biogas production process. Therefore, characterizations and analyses of different substrates have to be conducted to determine their suitability and profitability. Different analysis techniques include TS, VS, N₂ content and COD will be discussed. Macronutrients, micronutrients, and their function will be explained. Inhibitory behaviors of substrates such as heavy metals, ammonia, and hydrogen sulphide will be assessed. To determinate biological degradability and methane production, BMP test will be explained. Lastly, process parameters such as pH, temperature, and mixing condition will be discussed.

Total Solids and Volatile Solids Determination

To determine the water content in substrates, TS, which is represented in percentage, or DM, which is represented in grams per litre (g/L), is conducted. According to EN12280 and APHA 2540 B standards, a sample of the substrate is placed in the drying chamber at 103–105 °C until it reaches a constant weight. TS is calculated in Eq. 1 [34]. The disadvantage of this method is that volatile acids and alcohols cannot be detected due to their evaporation in a drying oven.

For determination of VS or organic DM (ODM), the sample is situated in a muffle furnace, first for 30 min at 220 °C, and then for 2 h at 550 °C [130]. VS is calculated in Eq. 2 [34].

$$TS = 100 \frac{m_2}{m_1}, \quad (1)$$

$$VS = 100 \frac{m_2 - m_3}{m_1}, \quad (2)$$

where m_1 is the weight of sample material before drying, m_2 is the weight of sample material after drying at 105 °C and m_3 is the weight of sample material after ignition at 550 °C.

Chemical Oxygen Demand

With COD, the maximum chemical energy in substrates is determined. It helps to calculate recovery energy from a substrate since bacteria convert chemical energy to the energy form of methane. Comparing to the VS method, this approach can be used more precisely to analyze the results because volatile acids and alcohols in the substrate can be determined. For COD analysis, the sample of substrate goes through a boiling mixture of sulphuric acid (H_2SO_4). Unreduced potassium dichromate ($K_2Cr_2O_7$) is evaluated to understand the consumed oxygen equivalent which allows the determination of energy content in substrates.

Macronutrients

The main biogas production step is in the methanogenic phase. To increase biogas yield, the substrate should be more suitable for methanogens than other bacteria. Biomass components can be assumed to be 50% C, 20% O, 10% H, 11% N, 2% P and 1% S. According to Bischofsberger et al.'s study [131] cited in [6], for substrate more suitable for methanogenic bacteria, the balance of macronutrients in an AD reactor should be 1000:5:1:1 (bCOD:N:P:S). If the substrate will be used for the hydrolysis phase, this ratio is around 350:5:1:1 (bCOD:N:P:S).

In the substrate, the C/N is an important parameter for the characterization of feedstock. The C/N ratio should be in a range between 16/1 and 45/1 for hydrolysis, and 20/1 and 30/1 for methanogenesis. If the C/N ratio is high, methanogenic bacteria quickly consume the available nitrogen for their cell synthesis, and carbon utilization will be limited. Therefore, the degradation process could stop. If the ratio is too low, nitrogen is converted to ammonia, which is inhibitory for AD because pH is increased in the reactor [132]. Table 9 shows the C/N ratio of some common substrates.

Table 9 The C/N ratio of some common substrates (adopted from [37, 132])

Substrates	C/N ratios
Potatoes	44
Whole plant ensilage	35–70
Grass ensilage (meadow grass, clover)	14–22
Straw (rice, wheat)	70
Whole grain	20–24
Waste from sawmills	511
Paper	173
Waste from households	18
Sludge	6
Dung (ducks, chicken, goats, pigs, sheep, cows)	8–24
Human excrement	8
Dung of elephants	43
Manure (cattle, pigs)	14–20
Rape press cake, cold pressed	9.5
Water hyacinth	25
Seed fines	> 200
Saw dust	> 200
Municipal solid waste	40

Micronutrients

Micronutrients are used for coenzyme creation by methanogenic and hydrolytic bacteria during biogas production. Lack of micronutrients is a limitation for AD processes. Methanogenic consortia need Ni, Co, Mo, Fe, Se and Wo while Zn, Cu and Mn are necessary for hydrolytic species [133]. If these conditions are not available, AD processes will be negatively affected. Generally, there are enough trace elements in the reactor if multiple substrates are used. However, the availability of trace elements could be limited in a reactor if it is fed only a single type of substrate. Trace element solutions may be added into a reactor to solve this issue. Cai et al. [134] stated that adding Fe, Mo, Se and Mn has significant effect on the reduction of VFAs and improvement of methane yield. Another recent study showed that supplementation of Co, Fe, Mo, Ni and Se increased the stability of the reactor in the single-stage and two-stage food waste digester system. This is due to the improvement of VFA/TIC and VFA concentrations in the reactor and methane yields were not only improved from 0.083 to 0.316 m³/kg VS in the single stage reactor but also maintained at initial levels, even though the loading rate reached 4 g VS/(L day) [135]. Li et al. [136] reported that the mono-digestion of *Pennisetum* hybrid failed at the OLR of 2.0 g VS/(L day) due to the accumulation of VFAs. Moreover, a recent study reported that the addition of natural zeolites increased the cumulative methane yield by 83% due to adsorbing a significant amount of NH_4^+ from the medium during the process [137].

Biochemical Methane Potential

The BMP test gives information about methane yield, biological degradability and inhibition possibility of a substrate. There are standards for this test such as EN 11734, VDI 4630 and DIN 38 414 (S8). To determine an unknown substrate's properties, the BMP test is simplified by Braun (DIN 38 414 (S8)) [138]. For a BMP test setup, a 0.5–1 L vessel is used as a digester. A weighed amount of unknown substrate and inoculum are mixed with water in a digester. Nitrogen or argon gases can be applied to create an anaerobic environment before sealing the digester. To fix the temperature, the digester vessel is placed in a water bath or furnace. Measurement of biogas is conducted using a water displacement method for this test. If only CH₄ content is wanted, an alkaline solution (2–4 mol/L NaOH) in a bottle will be placed after the digester. Its output gas is connected to a water displacement bottle to monitor CH₄ production. The production should be monitored daily. When the biogas production rate starts to reduce, the reading period can be done two or three times a week. If daily biogas generation is lower than 1% of the total biogas production, the test can be terminated [6]. For an unknown substrate, at least three vessels should be prepared for accurate the BMP test results. Moreover, three vessels should be used for blank (only inoculum) samples to correct the results for biogas generated by inoculum only. After the BMP test is done, pH has to be measured for each vessel to check the acidification level which gives information about inhibition. Possible biogas yield trends from a BMP test is represented in Fig. 10.

Inoculum

Anaerobically treated sewage sludge or animal manure can be used as inoculum for a standard BMP test. Adaptation of bacteria to a new substrate is essential for reliable BMP results. Therefore, before the BMP assay is set-up, inoculum can be acclimatized to a new substrate in a separate digester by introducing the new substrate gradually. As an inoculum source, sludge from operating biogas plants should not be

used because of potential inhibitor accumulation in the reactor. According to EN 11734, the sample of inoculum should be prepared with three main steps, which are the process of washing, centrifuging, and re-suspending. During re-suspending, a buffered medium and trace elements should be added to increase bacteria activity. The inoculum is stored at around 38 °C for a short time, and then at around 4 °C for the long-term. However, long-term storage is not preferable. Furthermore, some substrates should be added inside the inoculum to prevent the starvation of inoculum.

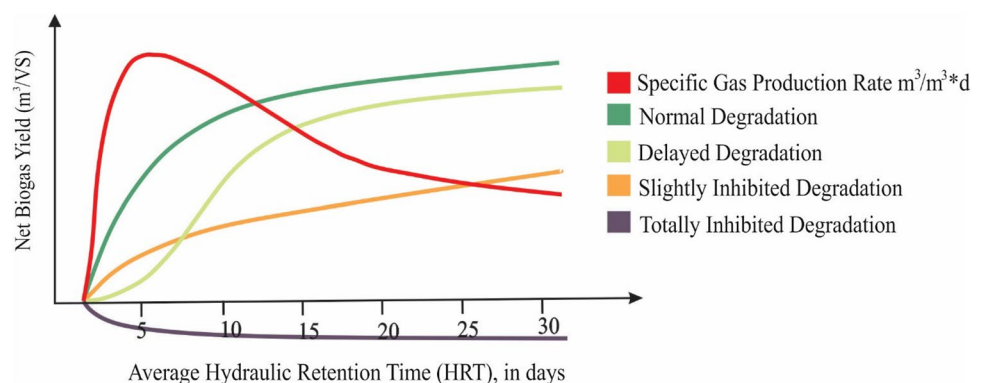
Substrate/Inoculum Ratio

To obtain an accurate result, the ratio of substrate to inoculum should be taken into account. The VDI 4630 standard gives a range that should be around 0.5 g/g for the ratio of VS_{sample} to VS_{sludge} [6]. When there is not enough substrate for inoculum in the reactor, the substrate degradation potential is underestimated. When it is very high, acidification may occur because of the accumulation of VFAs in the hydrolysis phase. A study showed that the ratio can affect the result considerably [139]. In the study, inoculum/substrate ratios of 1, 1.5, 2, and 3 were tested and the results revealed that the specific methane productions were 23 and 10 mL CH₄/kg VS for inoculum/substrate ratios of 1 and 3, respectively [139]. Zhou et al. [140] studied the ratio with soybean cake. The ratio range was between 0.33 and 10 and the results indicated that the maximum methane yield obtained the ratio between 1.11 and 1.67 [141]. Additionally, Córdoba et al. [142] investigated the inoculum/substrate ratio to be between 1 and 1.67 for swine wastewater treatment using a kinetic parameter equation. The highest methane yield was obtained for the ratio of 1 with a well-fitting curve.

Evaluation of the Biochemical Methane Potential Test

Organic substrates should be evaluated by their biogas yield to demonstrate their suitability for a full-scale AD

Fig. 10 BMP degradation curves (adopted from [9])



application. For this investigation, pH, TS or DM, VS or ODM, COD, ammonia nitrogen and BMP need to be determined.

To evaluate the results of the BMP test, the blank sample (inoculum only) and normal sample (substrate and inoculum) have to be compared. If the blank sample's biogas production is more than 20% of the substrate BMP test, it should be removed from the results according to VDI 4630. When biogas production from the blank sample is subtracted from biogas production from the normal BMP test, biogas production specific to the substrate is obtained. When daily biogas production versus time is graphed, the graph's slope can be evaluated to assess kinetics (rate) of biodegradation. If it has a high slope, the substrate is readily biodegradable, and if the slope is near the zero or negative, the substrate shows inhibitory behavior to inoculum as shown in Fig. 10. To obtain accurate BMP test results, a substrate which has lower water and less volatile content should be quantified by VS to represent the specific methane yield as mL methane/g VS. For a soluble substrate, the specific yield as mL methane/g COD is preferred. In both cases, methane volumes need to be corrected for standard temperature and pressure (0 °C and, 1 atm).

Process Parameters

Different bacteria and simultaneous biochemical steps are involved in producing biogas during the AD process. This complicated process is affected by several factors, such as pH, temperature, OLR, mixing conditions, reactor pressure and hydraulic retention time (HRT).

pH

One of the most crucial parameters during the AD process is pH, which directly affects reactor performance. pH has impacts on the growth rate of methanogenic bacteria and the breakdown of ammonia, sulphide and organic acids. Methanogenic bacteria generally work between a pH of 7 and 8 and the pH value should be fixed between 6.5 and 8 to optimize the entire system. There is an inhibition risk in reactors when the pH is below 6 or above 8.5 [34]. While degradation of proteins increases the pH value due to ammonia production, VFA accumulation has a negative impact on pH. The buffer system is controlled by the pH value in the digester. Thus, in the reactor, the pH value depends on the partial pressure of CO₂ in the gas phase and alkaline and acid component combinations in the liquid phase. The main biogas production occurs in the methanogenic phase and the suitable pH range for methanogenic bacteria is between 6.5 and 7.5. While their biogas production reaches the highest level between 6.8 and 7.6, the lowest production is below 6.3 pH and above 7.8 pH [138, 143, 144]. If substrate does

not contain alkalinity and/or contains high concentrations of organics with VFA accumulation risk, external alkalinity addition may be needed for both BMP assays as well as continuously-fed AD systems to maintain neutral alkalinity.

Temperature

Temperature is another key operational parameter for AD processes. Temperature is a factor of reaction velocity, chemical dissociation and physical diffusion. In biogas production processes, there are three ranges of temperature including ambient or psychrophilic (15–25 °C), mesophilic (30–40 °C) and thermophilic (50–60 °C). Methanogenic bacteria are more fragile than hydrolytic and acidogenic species. While methanogenic species at mesophilic temperature can tolerate ± 3 °C without any significant change of biogas production, methanogenic bacteria at thermophilic temperature are sensitive to even 1 °C of fluctuation and they need more time to adapt to a new temperature [34]. Moreover, the solubility of different materials such as NH₃, CH₄, and H₂S change with temperature. High-temperature water has less solubility than low-temperature water. Therefore, it can affect the inhibitory material in the reactor. Most AD systems operate at a mesophilic temperature because of the easy control of methanogenic bacteria and less energy demand required.

Mixing Condition

Mixing helps to balance pH and temperature and to prevent stratification and deposition of solids and scum in the reactor. It creates a uniform physical, chemical and biological environment. Moreover, it increases contact between the substrate and microorganisms and dilutes inhibitory substances which leads to improved biogas production. However, the mixing condition, either continuous or discontinuous can create a conflict [145, 146]. Mixing behaviour can be estimated by particle motions related to AD process parameters using computational fluid dynamics programs [147, 148]. Mixing can be divided into the three main groups, which are mechanical stringing, mechanical pumping and a gas injection system.

Mechanical stringing is the most common type of mixing. It consists of a propeller, a rod mixer, and a paddle agitator. The main drawback of this system is the wear of its components and consumption of more time and money required for repair. A mechanical pumping system takes substrate in a digester and sends it back with pressure. This creates a flow inside of the reactor. The disadvantage of the system includes a clog caused by substrates. A gas injection system injects procured biogas to lower the level of the reactor with pressure. The gas bubbles move upward in the reactor and create mixing [149].

Hydraulic Retention Time and Organic Loading Rate

HRT is the time duration that substrate stays in the reactor. OLR describes the maximum organic material that can be digested in the reactor per volume and time. HRT is calculated in Eq. 3 [34]. The whole process can fail because of too short an HRT. Generally, the average retention time is around 20–30 days under mesophilic conditions. Short HRTs may cause VFA accumulation, therefore, changing the pH. Short HRTs were studied in the literature and 89 and 97% of degradation was achieved in an HRT of 1.5 and 3 days, respectively [150].

$$HRT = \frac{V_R}{V_{fed}}, \quad (3)$$

where HRT is the hydraulic retention time (days), V_R is the reactor volume (m^3) and V_{fed} is substrate amount (m^3/day).

Reactor Pressure

Reactor pressure may have some negative impacts on biogas production processes as the partial pressure of different gases such as hydrogen and carbon dioxide do not only affect the microorganisms but also chemical reactions. For example, acetoclastic methanogens can be inhibited by H_2 accumulation. There is a very narrow pathway between the consumption and production of the H_2 microorganisms. H_2 concatenation should be in balance in the reactor and methanogenic bacteria need sufficient H_2 to produce CH_4 while H_2 should not excessively surround acetogenic microorganisms. The high H_2 partial pressure may lead to inhibit acetogenic microorganisms to produce H_2 . According to Junicke et al. [151], when the H_2 partial pressure exceeds 40 Pa without buffering materials in the reactor, biogas production decreases. The effect of H_2 partial pressure has been well reviewed by Leng et al. [152].

Light Effect

Deublein and Steinhauser [37] and Abbasi et al. [5] gave some explanations about the effect of light on AD processes. They mentioned that the light has strong negative effects on methanogenic bacteria; therefore, the process should be in absolute darkness. However, the authors could not find any information about which wavelengths have a negative impact on the bacteria. Moreover, the suitable wavelength might have some positive effects on the process such as the elimination of some harmful bacteria such as sulphate reducers and methane oxidizers. Therefore, this topic should be investigated further.

Conclusions and Future Trends of Biogas

This paper reviewed the latest trends and progress in biogas production technologies including potential feedstock. AD processes have gained great attention during the last two decades due to their positive benefits such as requiring low energy demand for the process, production of renewable energy, and improvement of waste management. Furthermore, different feedstocks from different regions can not only be used for an AD process but also biogas production can be implemented in small and large scales. The flexibility of biogas production makes it easy to implement AD processes all over the world. However, the process still needs some improvement including shorter HRTs and new substrate types, especially from waste and genetically modified crops. High rate bioreactor designs support organic substrate removal at shorter HRTs with a higher biogas yield. Two-stage or multi-stage bioreactors are used to overcome these limitations. Furthermore, a thermophilic system has benefits over mesophilic digestion; however, microorganisms' sensitivity and higher energy demands are drawbacks that have yet to be overcome.

Additionally, use of a single substrate may create an imbalance in the AD process, therefore, a co-digester is the best option to increase biogas yields and to keep the C/N ratio, and pH balanced, and reduce the HRT. Therefore, this approach decreases toxicity in the reactor. These novel approaches carry out the AD process effectively leading the process to become more profitable and an easy to replace fossil fuel-based energy sources. Recent developments of substrates include aquaculture, food waste, and agricultural waste, which are lignocellulose-based residuals. One of the substrates is animal manure which has bacteria that are able to hydrolyze lignocellulose content materials. Therefore, co-digesters gain attention from researchers due to enabling the use of energy crops, which have high methane yield and lignin content.

The methanogenic phase is generally the limiting step for an AD process while the hydrolysis phase becomes the limiting step when high lignin content materials are used. To increase the overall efficiency, and controlling and optimization of the AD process, the bio-reaction has to be well understood. Some microorganisms, which are involved in an AD process, have an adverse effect on methane yield such as methane oxidizers and sulphate reducers. Even though the AD process parameters are well established, there are some areas that require research in the near future such as light treatment effects as there is not currently data available for them in the literature. This may have some positive effects on the reduction of undesirable microorganisms. In addition to, it is the difficult to compare results with each other due to different units and all parameters that are not reported in

the literature. Therefore, a standard has to be established to distinguish between results of published papers.

Overall, biogas production and utilization are a great and promising pathway to reduce mankind's negative impacts on the environment and the use of fossil fuels. Policy makers should consider the unutilized significant potential of biogas production available and increase their support for biogas utilization. With continued efforts, biogas will be a significant solution for the reduction of GHG emissions, production of renewable energy, and management of waste disposal.

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