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A Review of Biogas Production from Small-Scale Anaerobic Digestion Plants

Raghad Maher Wadi*, Sroor Atallah Khalifa

Environmental Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

*Email: ecma016@uomustansiriyah.edu.iq

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Abstract

One of the most serious problems facing the whole world today is global warming. Their lease of greenhouse gases is exacerbating the effects of global warming. Reduced greenhouse gas emissions and searching for alternative energy sources are becoming increasingly crucial. This study aims to review that one of the effective methods for lowering greenhouse gas emissions is the creation of biogas from agricultural waste using anaerobic digester plants. A lab-scale 5-liter batch fermenter was incubated at room temperature, specifically mesophilic (35°C). Biogas is a clean, reasonably priced, and sustainable energy source produced by the anaerobic fermentation of waste and organic waste. Mixing sludge and waste to react with each other during biogas production is essential. Factors affecting biogas, such as loading rate, retention time, operating ambient temperature, pH, mixing, etc., are also discussed. Asia is a region where the generation of this form of renewable energy is widespread, particularly in nations like China and India. The generation of biogas never has any adverse environmental effects, but it also yields environmentally safe byproducts. Agricultural waste is a large and anthropogenic source of methane in the atmosphere. It can be converted into nutrient-rich fertilizer. Agricultural waste, food waste, animal or human manure, and other organic waste are all converted into energy (in the form of biogas or electricity) using anaerobic digesters. Another advantage of biological fermentation is that it leaves behind a high-quality organic fertilizer.

Keywords: Acetogenesis; Acidogenic; Anaerobic; Biogas; Digestion; Hydrolysis

1. Introduction

Fossil fuel sources played a vital role in the staggering increase in world energy consumption in the 1980s. Fossil fuels provided over 85% of the world's primary energy needs in 2018. The conversion of biomass into energy has increased in recent years, from 65 GW in 2010 to 120 GW in 2019, as a result of environmental concerns, energy costs, growing distributed generation, and climate change. Anaerobic fermentation of waste with high moisture content makes it easier to process and transforms landfill and fermentation technology. By the end of 2019, the capacity of biogas plants worldwide had reached approximately 19.5 GW. Due to the ease with which they break down and the amount of water they contain, most biogas comes from food, fruit, and vegetable waste from homes. Wet waste from cafes, restaurants, and daily markets is biogas's most common raw material. The classification given to these inputs is the organic component of municipal solid waste (OFMSW) [1]-[3]. Unlike fossil fuels, biogas is made from biomass, which is naturally renewable and acts as a virtual reservoir for solar energy through photosynthesis. In addition to improving the country's reputation as an energy superpower, anaerobic digestion (AD) biogas significantly contributes to resource conservation and environmental protection [4]. Biological matter naturally forms biogas. The main component of this biogas, methane, naturally enters the atmosphere and has a significant negative impact on global warming. In the last ten years, methane has been turned into electricity, fuel for cars, and heat, making it a vital fossil fuel [5].

Although natural gas resources still account for most current methane consumption and use, biomethane production through

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waste-to-energy technologies has increased significantly. From 2010 to 2018, production capacity increased by 4%. With a global production rate of 3.5Mtoe, there is a 700Mtoe potential for biomethane production. This output rate does not guarantee that methane can be produced entirely from renewable resources. Alternatively, the availability of specific equipment, control, and management systems is essential for developing biogas infrastructure. An industry can be established and commissioned to produce bioenergy from natural renewable sources [5]. Advanced large-scale plants using biogas are used in developed countries.

Biogas is often used to provide energy, heat, and electricity. Additionally, work is being done in many industrial applications for biogas plants to replace natural gas. Data analysis shows that biogas production is continuously increasing due to global policies and initiatives. The transport sector is expected to provide 0.5% or 12.8GW of renewable energy by 2020 [6], with biofuel production at several sites considered the primary funding source for this strategy. Notably, increasing biogas production should be avoided since it poses a risk to the food supply.

For this reason, cellulose and lignin wastes are mainly used for biofuel production. Over the last few decades, many countries have made significant strides in the global biogas market. Advanced biogas production technologies also receive national and international regulatory support, such as research, design, and development (RD&D) funding, grants, and guaranteed power purchase agreements, to compete against traditional energy suppliers and create a strong market [4],[6].

2. Biogas Production

Under hypoxic conditions, biogas, flammable, colorless gas, is produced by the biodegradation of organic substances. Biogas is generated from “biomaterials". Also, it is produced by the AD from biodegradable materials such as biomass, green waste from cow manure, and agricultural waste such as cassava and sugarcane. Most of the gases that make up biogas (H_2) include methane (CH_4), carbon dioxide (CO_2), and about 15% of other gases, such as hydrogen [7], describing the composition of biogas. Bacteria produce gas when organic matter is biodegraded under anaerobic conditions [8]. Biogas contains large amounts of methane, as presented in Table 1 [7].

Table1. Biogascomposition [7].

Component	Concentration (%)
Methane (CH_4)	55-60
Carbon dioxide (CO_2)	35-40
Hydrogen(H_2)	2-7
Hydrogen sulphide (H_2S)	2
Ammonia (NH_3)	0-0.05
Nitrogen(N)	0-2

For this reason, it is a desirable source of energy. Biogas can be used as fuel for cooking and heating in all countries due to the energy produced. Biogas can also be used in anaerobic digesters, which use gas engines to convert gaseous energy into electricity and heat. Indeed, the main components of biogas are the greenhouse gases methane and carbon dioxide, which are harmful to the environment. Therefore, burning it before releasing it into the environment is essential.

Methane can replace non-renewable fuel sources in producing heat, electricity, and transportation fuels, making biogas production a renewable energy source. As a means of lowering greenhouse gas emissions and advancing the sustainability of the energy supply, scraps, energy crops, and leftovers are gaining popularity in the modern day [9]. Anaerobic digestion is a popular method for stabilizing industrial wastewater, livestock manure, municipal solid waste, and sewage sludge because it is effective. There are only a few benefits of anaerobic digestion technology, including weight reduction, pathogen reduction, energy consumption reduction, odor removal, and, most importantly, energy recovery from methane [10]. Anaerobic digestion aims to biodegrade organic materials in an oxygen-free environment to produce methane-rich biogas. Aerobic digestion is an inexpensive and environmentally friendly waste treatment method. This technique reduces greenhouse gas production.

Meanwhile, it reduces and stabilizes waste. The capacity of aerobic digestion to process a range of organic materials is one of its key advantages. The biogas produced could be refined and used as a fuel for automobiles in the transportation sector, or it can be used to produce electricity and heat. Another byproduct of AD that can be used as a fertilizer for soil is called “decomposing residue” [11]. Different processes, divided into dry and wet fermentation systems, can be used to generate biogas. Depending on the source of raw materials, vertical agitator digesters with different types of agitators are commonly used in wet digester systems. A dry digester or high solids AD system generally processes feedstock with greater than 15 percent solids content. The feedstocks for a dry digester are often described as stackable. Wet digester so low solids AD system generally processes feedstock with less than 15 percent solids. The feedstock for a wet digester is typically in slurry form and can be pumped [11].

2.1. Anaerobic Digestion

Anaerobic digestion is a biological process that uses microbial populations to break down organic matter without oxygen. As shown in Fig. 1, AD can be divided into four steps: hydrolysis, acidogenesis (in which acid is produced), acetogenic (in which acetic acid is produced), and methanogenesis (in which methane is produced) [12]. To raise the calorific value and reduce undesirable components, such as H_2S, and CO_2, which are potentially destructive to user systems, it is vital to purify the raw biogas and transform it into a high-quality standard fuel. The term "biogas purification and upgrading" refers to this process [13]. Renewable Natural Gas (RNG) is like natural gas produced from non-renewable fuel sources. Methane accounts for 90% or more. Natural gas can replace RNG, power fuel-powered vehicles, and feed into the natural gas grid. Upgrading biogas to biomethane is considered a technology that has gotten much attention in the bioenergy industry [12]. Biogas has the potential to become a significant player in the growing renewable energy market. Global use of biogas is expected to double over the next few years, from 14.5 GW in 2012 to 29.5 GW in 2022 [12].

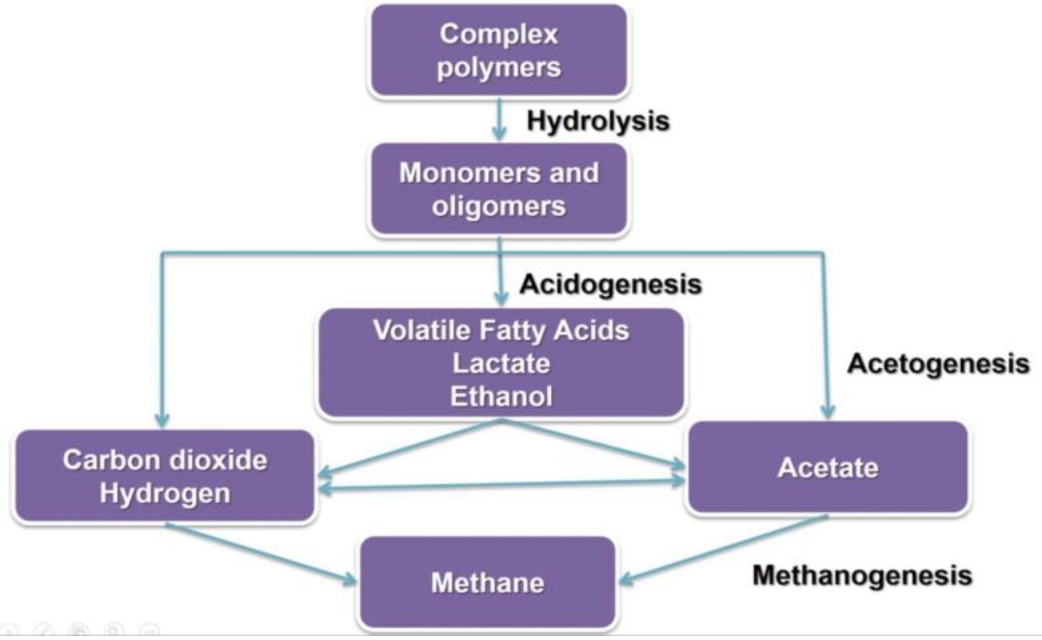

Figure 1. Anaerobic digestion stages [12].

2.1.1. Hydrolysis

Organic biomass used in anaerobic digesters often contains complex polymers unavailable to microorganisms unless further degraded by hydrolysis or other pretreatment processes [14]. As a result, hydrolysis works to break down organic macromolecules into their smaller parts, which acid-producing bacteria can then use. Although hydrolysis can be an electrochemical process, it mainly occurs as a biological process during anaerobic digestion. Hydrolytic bacteria may produce long-chain fatty acids (LCFAs), amino acids, and sugars from lipids, proteins, and carbohydrates when extracellular enzymes are released during hydrolysis [15]-[17]. The resulting hydrolysis can be propagated across the cell membrane of acid-producing bacteria following enzymatic cleavage.

It should be noted that some substrates, such as lignin, cellulose, and hemicellulose, can be difficult to degrade. It is not suitable for microorganisms due to their complex structure. Hydrolysis may be a defining process rate, even though prior research has demonstrated that methanogenesis might be a rate-determining phase dependent on the ratio of methanogenic to hydrolytic bacteria. Given how vital hydrolysis is to the speed of anaerobic digestion, people have been very interested in finding ways to speed up hydrolysis in anaerobic digesters.

In particular, for digesters that digest highly lignocellulosic wastes, several waste pretreatment techniques are being explored and used to maximize hydrolysis [18]. There is no indication of increased hydrolytic activity below pH 7 [19], and hydrolysis is most effective between 30 and 50 degrees Celsius with a pH of 5 to 7. To hasten the hydrolysis of these sugars, enzymes are often included.

2.1.2. Acidogenic

Bacteria can manufacture volatile fatty acids (VFAs) and other chemicals using their cell membranes to hydrolysis byproducts. Organic acids fall within the category of volatile fatty acids. Larger organic acids like propionate and butyrate are also included. It is usually in ratios between 75:15:10 and 40:40:20 [20]. Even ethanol and lactate can be traced. The digester conditions can affect the exact concentration of intermediates produced in the acid generation step; VFA concentrations have been reported to vary substantially for digesters operating at various pH values, with many publications showing seemingly conflicting results. With acidogenic bacteria having fewer than 36 hours of regeneration, acidogenesis is generally thought to progress more rapidly than all other stages of anaerobic digestion. Acidification of VFAs is generally considered to cause breakdown tank failure even though VFAs formation produces direct precursors of the final step of methanogenesis. Bokashi is a Japanese term that means “fermented organic matter,” which is the process of turning food scraps and kitchen waste into compost, it’s an easy, fast process and produces no foul odor [21],[22]. In the bokashi composting process, the leftovers and a microbial inoculant are broken down anaerobically to generate a very acidic final product. These items are versatile enough to be employed as liquid or dry fertilizers. [22]. At last, it’s reasonable to think about the process of making VFAs from amino acids in protein-rich waste, such as wastewater. Additionally, single amino acid degradation is possible in the presence of hydrogenotrophic bacteria. However, this process is slower than the Stickland reaction [23]. The Stickland reaction is primarily described as a biochemical event where inorganic molecules are oxidized or reduced simultaneously to produce distinct biological compounds [23]. Amino acids usually break down into pairs of VFAs via the Stickland reaction. Deamination makes ammonia, which is a necessary byproduct of amino acid breakdown. At high enough concentrations, ammonia is also a potent inhibitor of anaerobic breakdown [23].

2.1.3. Acetogenesis

Part of the original substrate was transformed into a suitable substrate from plastic by synthesizing acetate during acidogenesis. However, other higher-yielding VFAs have not yet been delivered to pathogenic bacteria. These higher VFAs and other intermediates are converted to acetate, producing hydrogen [24]. Hydrogen transfer between specificities, an attractive interaction observed during anaerobic degradation, is driven by hydrogen generated during acetogenesis. Although acetogenesis produces hydrogen, acetogenic microorganisms are negatively affected by high partial pressure. However, hydrogen can be rapidly consumed while maintaining a partial pressure favorable for acetone generation by inducing an exudative reaction since atrophic hydrogen methanogens are present [25]. Simultaneously, lipids undergo another acetogenesis generation process called acidogenesis, in which glycerol is converted to acetate by acidogenesis, and LCFAs are converted to acetate by oxidation. It is helpful to remember that only LCFAs with an even number of carbons can degrade to acetate; LCFAs with an odd number of atoms first degrade to propionate.

2.1.4. Methanogenesis

Methanogenesis is the last stage of anaerobic digestion, during which methanogenic bacteria use available intermediates to create methane [26]. Methanococcus volts and Methanococcus Vannelli cells were exposed to oxygen for ten hours. After that time, 99% of the cells had died. Methanogenic microorganisms are obligate anaerobic microorganisms. In addition to being sensitive to oxygen, methanogenic bacteria are restricted to several substrates. The production of methanol, methylamine, and format has also been reported [27]. Typically, hydrogenotrophic methane creation makes up the remaining one-third of methane synthesis, with around two-thirds coming from the methane of plastic methanol from acetate. However, some studies have also observed the formation of methanol, methylamine, and format [27]. A higher pH is often necessary for methanogenic bacteria than in previous phases of anaerobic digestion. A lower redox potential is also necessary, which calls for secondary two that have proved very challenging to create in a lab [28]. Methanogens also appear to regenerate more slowly than other bacteria during anaerobic digestion, from 5 to 16 days.

2.2. Classification of Anaerobic Digestion Plants

The quantity of raw material input, gas output, or, if additional energy conversion is desired, a thermal unit’s electrical or heat output can all be used for AD installation classification [29]. The ranges described by these labels do not have any mathematical foundation. In the study literature, the phrases “micro,” “small,” “medium,” and “big” anaerobic decomposition base “large” have often been employed [30], with some countries developing their catalogs. In the European context, these classifications are related to FIT payments, which are determined by the amount of electricity a plant produces.FIT (Feed-InTariffs) is a national policy framework that provides incentives and long-term contracts for renewable power plants based on the volume of energy they produce [30]. Since small and medium-sized projects have higher generation costs, fees are often based on the plant size regarding installed power capacity.

2.2.1. Micro-Scale AD (CHP Electrical Output < 15kWe)

Micro-scale anaerobic digestion systems are thought to only be useful for processing very tiny volumes of organic waste. On-site heating and home uses are made of the produced biogas Walker, Theaker, Yaman, et al. (2017). Small-scale anaerobic digestion 5 was interpreted in this analysis as a plant having a cogeneration capacity of 5 to 15 kWe, or equivalent. This study's scope is equivalent to prior micro AD research studies [31]. The treatment of tiny volumes of organic waste by microscale anaerobic digestion systems is thought to be their only use, with the resulting biogas being utilized for home and on-site heating. In this research, a power plant with a cogeneration capacity of 5 to 15 kWe, or equivalent, was designated as a small-scale anaerobic digestion facility using Walker's criteria. This range agrees with findings from previous microscopic DA investigations [31],[32].

2.2.2. Small-Scale AD (SSAD) (CHP Electrical Output Between >15 and < 99kWe)

SSAD systems often serve farm-scale applications and have sizable net energy (heat and power) production based on biomass in such agricultural situations. For more perspective, consider that the anticipated annual energy production from producing and digesting maize on a typical EU 28 farm would range from 431 to 586 MWe. The cogeneration capacity associated with this method ranges from 49 to 67 kWe. This scenario is based on methane production of between 7,500 and 10,200 m^3/ha, an energy density of 10.49 kWh/m^3 CH_4, a CHP electrical efficiency of 40%, and an uptime of 85% [33]. Based on these data and other publications, CHP power capacities ranging from 100kW are considered appropriate for detecting SSAD.

2.2.3. Medium-Scale AD (CHP Electrical Output Between >100 and < 299kWe)

The big utility systems and the aforementioned small-scale plants are separated by factories, referred to as medium-scale AD systems. The systems in this research that have a cogeneration capability of 100 to 300 kWe and can produce enough energy to support the demands of a small community are referred to as medium-scale AD plants (i.e., 15 to 300 kWe) [34].

2.2.4. Large-scale AD (CHP electrical output > 300kWe)

Based on a thorough review of the academic and industry literature on AD systems, large-scale systems are generally defined as plants with an electrical capacity of more than 300kW and raw material consumption above 5,000 tons. Each year. Recent major AD works in France have been accompanied by larger plants, with an average annual plant capacity of the sites of 115,400 tons [35]. Even though it can be harder to keep and run large facilities, economies of scale often make them more cost-effective [35].

3. Types of Small-Scale Anaerobic Digesters Plants

All AD systems have the same basic functionality. However, the design can vary considerably depending on location, raw material source, climates, and overall reactor usage, such as reducing organic loads, energy production, or bacterial concentrations [36]. These systems' main groups are passive, low-flow, and high-flow systems. This section discusses the different digester types and how they are used in the real world.

3.1. Passive System

A facility that integrates a biogas recovery unit with an existing manure or waste digester is called a passive system. Rarely, if ever, does this system require additional heating or mixing. Operating in psychrophilic and mesophilic temperature ranges, temperature parameters often exhibit seasonal trends. These units are commonly found in warm areas because methane production drops below 20°C. An illustration of a passive system is a covered lagoon digester.

3.1.1. Covered Lagoon Digester

A composting pond with an impermeable cover is all that covered digesters. Two lagoons operate in succession to form the system. Depending on the storage needs of the operation, the liquid level in the second lagoon may increase or decrease while it remains constant in the first lagoon. The stable environment of the first lagoon favors substrate degradation, and the resulting biogas is usually collected under a flexible cover and evacuated by a collection device. The added benefit of this setup is that it acts as a pre-spreading manure storage system, shown in Fig. 2. Diluted waste can be converted to biogas inadequately designed, covered, compacted digesters. One of the most common methods for digesting agricultural waste and manure sludge is covered compaction digesters, especially in North America [37]. Despite being the most inexpensive AD systems available, these devices are seldom employed in Europe because they need warm temperatures to maintain a digester temperature favorable for development.

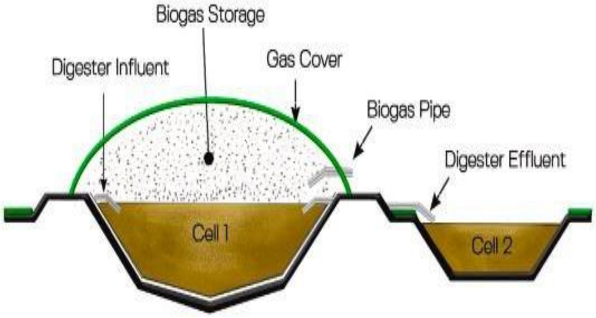

Figure 2. Covered lagoon digester [35].

3.2. Low-Rate Systems

A low-throughput system stores feedstock in the digester for lengthy periods (usually 10-30 days) to optimize biogas output. These apparatuses are functional in thermophilic (25-40 degrees Celsius) and thermophilic (50-65 degrees Celsius) temperature ranges. However, additional heating must be used to maintain the proper temperature, usually in the form of a heat exchanger [37]. For farming, the thermophilic temperature range is usually chosen unless manure needs to be pasteurized to reduce the number of bacteria [38]. Compared to thermophilic systems, thermophilic systems can often provide enough attenuation with less energy [36]. Three low-flow systems (garage-type, plug-flow, and full-mix) are discussed here.

3.2.1. Garage-type digester

Garage-type digesters use batch-mode dry fermentation with a sump tank, a microbial-rich liquid produced by the interaction between the feedstock and the microbial community in the plant. Anaerobic digestion [39]. The digester is constructed like a small garage, allowing the addition or withdrawal of raw materials in batches. The raw material is digested before each feeding cycle to ensure that pathogenic bacteria are in the best possible condition, thus speeding up the warm-up process; shown in Fig. 3 [40]. Depending on the yield targeted by the plant, the permeation circuit can be active continuously during fermentation or only occasionally [41]. Temperatures are maintained in the garage-style digesters using an integrated system that heats the walls and floors of the digesters. It allows them to operate within the thermophilic [41]. Material flow treatment with a high total solids (TS) ratio (TS > 15%) is suitable for these types of digesters. Since there is no need to mix materials in garage-type digesters, materials with higher contaminant content can be accepted. Due to the clogging of pumps and agitators, these contaminants can be detrimental to other digesters.

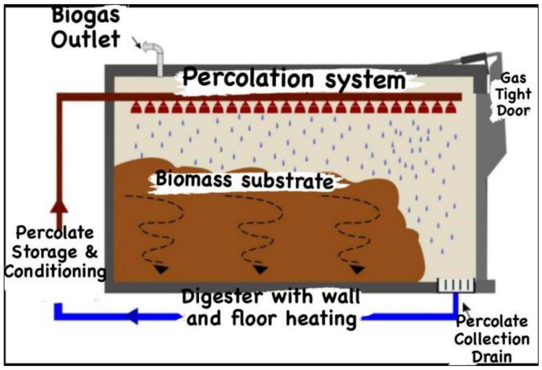

Figure 3. Schematic drawing of a garage-type digester [40].

3.2.2. Plug-flow digester

There is no longer any requirement for mixing in a flow digester, which consists of a rectangular tank in which the substrate is continuously exchanged in a horizontal motion (Fig. 4). An equal amount of old material added to the digester is replaced by new material ejected from the discharge point [42]. Therefore, to ensure that all substrates have the same hydraulic retention period when fresh feed material arrives, it pushes it through the digester like a “button,” forcing the oldest material to be discharged. The biogas is collected through an external, extendable gas collector installed on the digester’s roof [43].

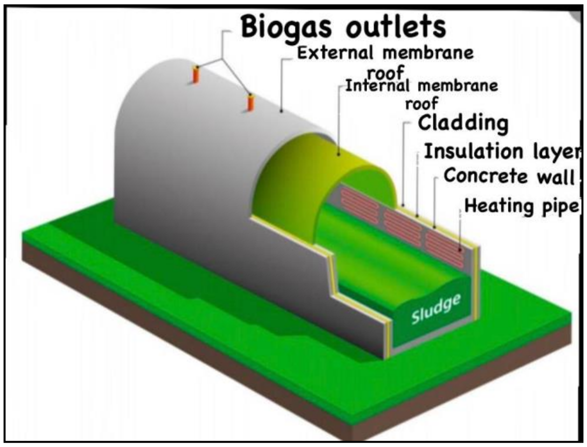

Figure 4. Diagram of plug-flow digester [42].

3.2.3. Complete mix digester

The essential component of the master mix digester is the continuously stirred tank reaction (CSTR), a circular, insulated tank made of reinforced concrete or heated steel. The digester components are further mixed to produce active microbiomass (Fig. 5). An equal mass leaves the digester for each volume of substrate entered. Continued biogas generation is possible if the amount going into the digester is modified to keep the retention period between 20 and 30 days [44]. The fully mixed digester can handle a wide range of wastes, including those with total solids concentrations of 3–10%, dairy cow manure, processing waste, and pig manure. To maintain the solids in suspension, their agents in the reaction vessel can be stirred intermittently or continuously. Mechanical rotors, liquid circulation, or gas circulation are some examples of the types of mixing systems that can be used [43]. Using a two-phase arrangement instead of a single-phase can improve the performance of a fully mixed digester [45]. In this setup, bacterial fermentation breaks down raw materials in the first stage, and methanogens turn organic acids into biogas in the second stage [44].

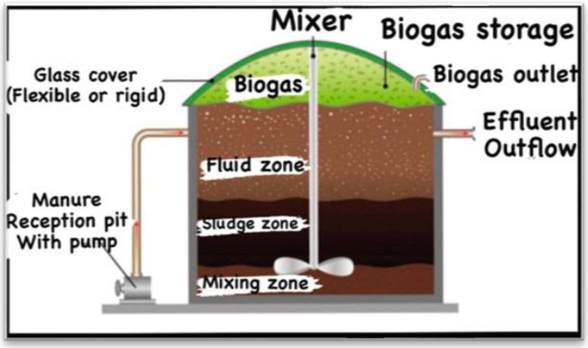

Figure 5. Schematic drawing of a fully mixed digester [44].

3.3. High-Rate Systems

The system operates at a high rate when the solids are kept in the digester longer than the liquid feedstocks with low energy density [44]. More microorganisms can fit in the reactor per unit volume, reducing the retention duration to 10 days. Increased biogas output and a reduced need for reactor space are two outcomes that result from the decision to keep the methanogenic bacteria. Two typical high-throughput systems are integrated film reactors and fixed membrane breakers.

3.3.1. Fixed film digester

A bioactive media reactor, which increases the surface area for bacteria to proliferate, forms the basic architecture of the immobilized membrane digester. That way, the hydraulic retention time (HRT) is reduced while generating a sufficient amount of biogas. When the necessary AD microbiota was immobilized as a biofilm, the slower-growing cells were protected from being washed away, leading to a biomass retention time unrelated to hydraulic retention. The reactor’s increased microbial biomass per unit volume allows for shorter hydraulic retention durations, generally 2-6 days. The main disadvantage of stationary membrane digesters is the possibility of medium clogging due to the high solids concentration of the input material [46]. This disadvantage is avoided by regularly feeding the material into the solid separator to filter out debris before entering the digester. The solid separator determines the efficiency of the digester, so the inlet concentration must be varied to maximize the separator’s efficiency (usually at 15% TS). Some potential biogas generation is wasted because carbon-rich particles must be removed to fulfill the size criterion. When space is at a premium, the compact size of fixed membrane digesters is a significant advantage over traditional digester; shown in Fig. 6 [46], [47].

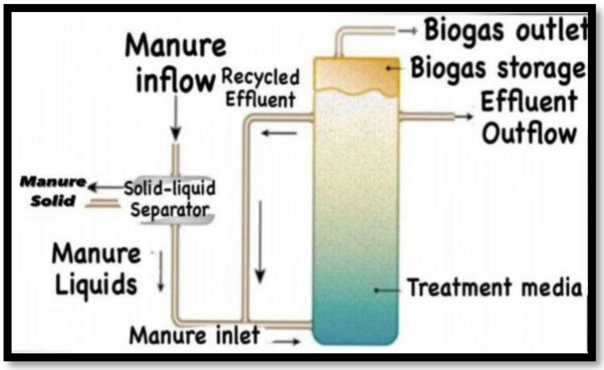

Figure 6. Schematic drawing of fixed film digester [46].

3.3.2. Suspended media digesters

Smaller particles are washed away by the continuous upward liquid flow of the suspended media digester, while larger particles are retained in the digester (shown in Fig. 7) [42]. Around the larger particles, microorganisms create biofilms, increasing the amount of methanogens in the reactor [44]. Upflow anaerobic sludge beds (UASB) and inductive media digesters are the most common sludge media digesters; the main difference is the dry matter level of the raw materials involved. While medium-induction reactors work best with highly concentrated waste streams (6-12% TS), the UASB is more suitable for dilute effluents (3% TS).

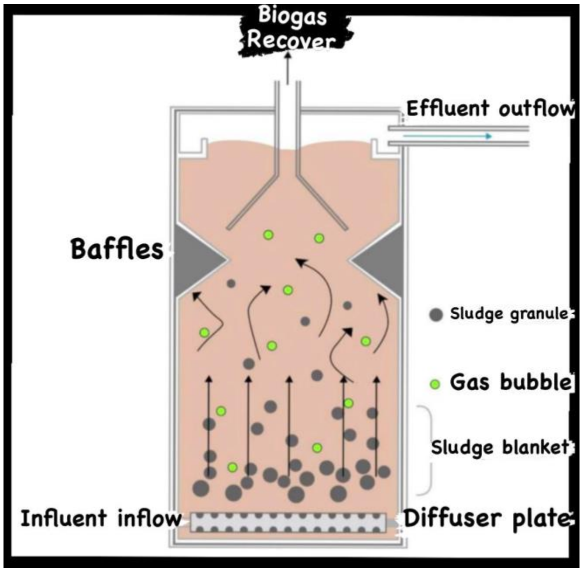

Figure 7. Schematic drawing of the suspended media digester [42].

4. Reactor Design Considerations and Operational Conditions

The following factors should be considered when choosing the best biogas plant design.

- Base dry matter (DM) content: Both dry and wet decomposers (DM 12%) are acceptable.

- There are three different types of feedstock: batch feeding (where no substrate is added), semi-continuous (where at least once per working day), and continuous (feed).
- Single-phase processes (all steps in the same reactor) and two-phase processes are available (hydrolysis and methanol generation take place in separate reactors).
- The temperature of the process varies from thermophilic (37 to 42 degrees Celsius) to thermophilic (50 to 60 degrees Celsius).

4.1. Lab-Batch Reactor Design to Examine the Yield of Biogas

Generally, batch or continuous modes can be used to estimate biogas potential. Because they are simpler and easier to monitor and evaluate, batch systems are more widely used. These tests are based on the same idea: to measure the amount of biogas or methane produced. The basic strategy is to incubate the waste using an anaerobic inoculum and monitor biogas generation. This method examines the biochemical methane potential of untreated and treated waste.

In this study, a lab-scale anaerobic digester was designed in the Water Treatment Laboratory at Mustansiriyah University, College of Engineering, which consists of some parts as shown in Fig. 8.

4.1.1.Apparatus Used:

The parts of the apparatus consist of the following:

1. Two pieces of Teflon cover
2. 5 liters plastic vessel cylinder shape of high-quality
3. pH meter
4. biogas output pipe
5. mixture (distilled water and agricultural waste) output pipe
6. metal septum
7. lab glass bottle for biogas collection
8. Graduated beaker for collection of displaced water

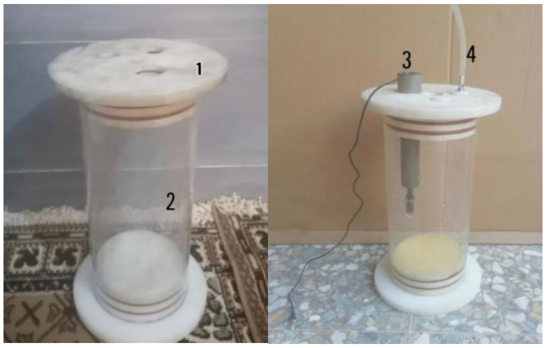

Figure 8. Designing of a biogas digester (from left to right).

4.1.2. Properties of plastic vessel cylindrical shape:

The plastic vessel has the following benefits

1. It can endure high and low temperatures because it is composed of high-quality materials.
2. It may be used repeatedly and has a sturdy construction that resists cracking and damage.
3. Long Service Life: it is easy to clean and has a long service life.

4.1.3. Properties of Teflon cover:

The benefits of the Teflon cover are:

1. Exceptional heat resistance
2. Excellent resistance to hydrolysis
3. High wear resistance
4. High tensile strength
5. Excellent dimensional stability.
6. Designed breathability and vapor
7. Easy to clean.

4.2. Process Phases

Both single-stage and two-stage (multi-stage) anaerobic systems can be used to operate biogas plants [48,49]. After weighing the pros and cons of each alternative, a decision can be made to operate the biogas plant using a single or multi-stage system.

1. Cost: Compared to single-stage systems,multi-stage systems are more expensive to install and maintain.
2. Operational parameters: Due to the different operating characteristics of the multiple stages, the ideal microbiological operating conditions in the multi-stage system are more demanding than the ideal operating conditions of microorganisms in a multi-stage system. On the other hand, there is better process control because the stages are segregated.
3. By using multi-stage systems, the stability of anaerobic digestion is increased. Methanogenesis is extremely sensitive to variations in organic loading rates, the heterogeneity of biodegradable raw materials, and the environment. Due to more effective control of these conditions and more uniform biodegradation load flow

from the first digester to the other,multi-stage systems are preferred over single-stage systems [50].

4. In terms of efficiency in removing volatile particles and improving biogas quality (methane content), the multi-stage system performs better than the single-stage system. Due to their simplicity,single-stage systems continue to be the most favored.

4.3 Process temperature

Microbial performance is directly affected by temperature, which is an essential factor inside the reactor. Biogas plants can operate at psychrophilic (25°C), mesophilic (32-42°C), or thermophilic (50-57°C) temperatures depending on the type of microorganisms. Methanogens are the most environmentally sensitive bacteria of all types [51]. Most species performed optimally under thermophilic conditions at 37°C, with no significant difference in other temperature ranges [52]. The temperature inside the reactor affects the reaction's kinetics and the microorganisms [53]. An increase in temperature increases enzyme activity over the optimum temperature range. However, exceeding this specified optimum temperature can inhibit enzymatic reactions. Most of the preferred enzymes work best at 37°C [54],[55]. Streitwieser [56] states that the thermophilic range is the superior choice for readily biodegradable substrates, increasing biogas production and reaction rates. In addition, modern biogas plants operating under thermophilic conditions require shorter warm uptimes [57]-[58]. The temperature must be kept constant for regular biogas production [59].

4.4 Mixing

The anaerobic process in the biogas plant is strongly influenced by the agitation (mixing) mechanism. The primary responsibilities of the agitation system are:

- Mixing the new and old media allows the digester's biodegradable media, temperature, and pH levels to stay the same.
- Improve the stability of anaerobic processes and microbial metabolism. Furthermore, at high total solids values, the mixture helps air bubbles back up from the biodegradable feedstock [60],[61].
- Reduce sediment production at the bottom of the digester to maintain the largest possible volume for anaerobic digestion and reduce the need for septic tank cleaning, usually done every 4 to 7 years [62].
- Remove the foam backing from biodegradable substrates. The formation of this layer can prevent 20-50% of biogas production [63]. Foam is usually the gas dispersion in a liquid containing a significant amount of gas (about 95%). Between the bubbles is a thin film containing the liquid phase [63]. The surfactant and the substance surfactant subgroups of surfactants are considered responsible for foaming. Biosurfactants are thought to produce microbial activity, while surfactants are molecules that enter the digester with food [47]. These foam layers must be removed as they cause operational disruptions, equipment damage, and costly losses due to reduced biogas production.

The main mixing methods are used in large-scale biogas production mixing technology. According to the structural concept of the digester (full mixing, nodal flow, or discontinuous concept), biogas plants can operate with or without mixing. While plug-in flow digesters are suitable for a range of 11% to 13%, full mixed digesters are commonly used for biogas installations with a biodegradable substrate with a total solid of 2% to 10% [63]-[67].

5. The Conditions Inside the Reactor

5.1 Oxygen

Oxygen leakage in the reactor can affect the anaerobic microbial groups of acetogenins and methanogens. It could lead to inhibition [68]. On the other hand, micro-dialysis can increase the efficiency of the hydrolysis step in methanation. The amount of H_2S in biogas was reduced (from 6000 to 30ppm) by adding microbial oxygen to 50-liter anaerobic digestion reactors. Bothejuet al. [68] demonstrated that an increase in oxygen leads to a decrease in methane potential through experimental and modeling results.

5.2 pH

Anaerobic digestion involves many different groups of microorganisms, each having an optimal pH value for their optimal growth rate. For example, the acidogenic group prefers a pH range of 5.0–6.0, while the methanogen group prefers a pH range of 6.5–8.0 [69]. Sibiyaand Muzenda [70] studied the combined effects of pH and temperature on the anaerobic decomposition of silage. The results showed that pH 6.5 and temperature 45°C produced the highest performance. The pH range that biogas plants typically operate in is 6.5 to 8.4. Mpofu and Coauthors (2019) summarize the ideal temperature and pH levels for various acetogenic and methanogenic bacteria. The amount of VFAs (volatile fatty acids), ammonium, and alkalinity significantly impact the pH value. The decrease in pH is due to an increase in VFAs.Conversely, an increase in alkaline sources is used to increase pH.

5.3 Organic Loading Rate (OLR)

Without a carefully calculated organic load ratio, achieving maximum cost-effective biogas production (OLR) is impossible. The OL Represents the amount of volatile solids loaded per unit of time and volume of the digester. Biogas production efficiency can be reduced if OLR is kept low. On the other hand, the inhibition of the process can be caused by a high organic loading rate. The OLR should be calculated based on the feed substrate to achieve the best conditions for the particular biogas plant. Rohstoffe (2012) has mentioned the equation of OLR as shown below:

$$\text{OLR} = \frac{m*C}{VR*100} \text{ (kg oDM m}^{-3}\text{ d}^{-1}) \qquad (1)$$

Where (m) is the amount of substrate fed in a unit of time (kgd^{-1}), (c) is the concentration of dry organic matter (% ODM), and (V_R) is the reactor volume (m^3).

5.4Hydraulic Retention Time (HRT)

One of the factors used to calculate digester volume is hydraulic retention time (HRT), which determines how long the material will remain in the digester before being emptied. Optimistic biogas generation can be achieved depending on the substrate used at different HRTs [71], as shown in the equation below:

$$HRT \ = \frac{VR}{V} \ (d) \qquad (2)$$

Where (V_R) is the reactor volume (m^3), and (V) is the substrate volumetric feed rate in the reactor, daily (m^{3}d^{-1}). Different HRT was evaluated using published research to obtain the best value for different substrates. The HRT used varies in length from 0.75 to 60.00 days. According to some studies, the ideal duration of HRT should be between 16 and 60 days.HRT should not be less than 10 to 25 days to avoid the washout of microorganisms required for the process. In different HRTs, Kaosol and Sohgrathok [72] used aquatic waste as anaerobic digestion media (10, 20, and 30).

5.5 Dry Matter Content of the Biodegradable Feedstock

The biodegradable substrate's total solids or dry matter content is closely related to the raw material. These parameters are vital when choosing a method for stirring, a design for the digester or reactor, and a fermentation method (dry or wet fermentation).

- Dry fermentation happens when the DM level is high, and wet fermentation happens when the DM level is less than 15%.
- The dry matter concentration significantly affects the agitation time of the digester (both in terms of technique and time). An essential factor in regulating viscosity and Bingham yield point is the dry matter content of the biodegradable raw material [73].
- The dry matter content of biodegradable raw materials can impact biogas generation.

Most large-scale biogas plants operate by wet fermentation, with less than 12% dry matter content. The total installed capacity of biogas plants worldwide at the end of 2019 was 19.5 TWh [74]-[76]. Most biogas plants still use wet fermentation.

5.6 Challenges Affecting Anaerobic Digestion

1. Co-digestion: the high biodegradability of food waste makes it a promising organic substrate for AD. Co-digestion of food waste with manure, sewage sludge, and lignocellulosic biomass could be beneficial due to the dilution of toxic chemicals, enhanced balance of nutrients, and synergistic effect of microorganisms [77].
2. Addition of micro-nutrients: The availability of trace elements, which provide micro-nutrients to microbes in AD, plays an important role in the performance and stability of food waste digesters. Essential trace elements include nickel (Ni), cobalt (Co), molybdenum (Mo), iron (Fe), selenium (Se)for methanogens, and zink (Zn), copper (Cu), and manganese (Mn) for the hydrolytic bacteria [78].
3. Control of foaming: Foaming in anaerobic digestion is a complex,three-phase phenomenon caused by surface active materials or surfactants (solid and soluble constituents) in the substrate, liquids in the digester, and biogas produced in the digester. When foaming occurs, the biogas produced is no longer released to the gas phase but dispersed in the liquid [77].
4. Multi-stage systems: Improving digester designs and operating strategies is another important aspect to enhance the OLR, methane yield, and stability of AD systems fed with food waste [78].

5.7 Inhibition of Anaerobic Digestion

1. The presence of other ions: Mg^{2+}, $Na^{+,}$ and Ca^{2+}, due to the existence of other ions, resulting in the decline of the toxicity of ions [79].
2. Toxic substances: Sulfates and other sulfur oxides are easily reduced to sulfides during anaerobic digestion. When the soluble sulfide reaches a certain concentration, the aerobic digestion process is mainly due to the production of methane processes [80].

In addition, there are other inhibitions of AD, such as temperature and pH, mentioned above in sections (4.3) and (5.2).

6. Agricultural waste

Agricultural waste is garbage produced at agricultural sites due to agricultural operations. An agricultural facility produces a wide range of garbage during normal operations. These are the liquid or solid byproducts of agricultural practices, such as animal excrement, crop residue (such as maize stalks), pesticides, and fertilizers [81]. Since agricultural waste can potentially affect the ecosystem substantially, it has recently received more attention. However, it can also be utilized for various positive purposes, such as fuel for energy production [82]. This process is particularly true in some countries, like India, which has a large cattle industry and a 6% annual growth rate. Effective byproduct utilization immediately impacts the economic and environmental damage to the country. Underuse or non-use of byproducts results in missed revenue possibilities and high costs for eliminating these items from the system. Most animal agriculture waste in affluent nations consists of pig dung, but in many developing countries, particularly in Southeast Asia, cow manure is the norm [81]. With the help of anaerobic digestion, these wastes may be converted into biogas, a sustainable energy source of at least 50% methane. The remaining solid residue can be used as nutrient-rich fertilizers. The ability of anaerobic digestion to convert a wide variety of biomass sources such as organic waste, slurry, and manure into highly energy biogas makes it an attractive valorization technique. Anaerobic digestion, which dates back to the 10th century BC when Assyrians utilized methane to heat their water, is used by farms worldwide.

6.1. Crops Waste Digestion

Anaerobic biodegradation is highest for inedible crop residues from food crops (such as leaves and plant wastes) and residues from crops specifically for energy (such as maize, tubers, cabbage, and wheat). Cell walls and their major components, like lignocellulosic substances, cellulose, hemicellulose, and lignin, comprise most plant biomass. Cellulose is a linear polysaccharide polymer of glucose (1, 4 glucans). Hemicellulose has a shorter chain than cellulose, with 500 to 3,000 sugar units per polymer compared with 7,000 to 15,000 glucose molecules. While cellulose is an unbranched polymer, hemicelluloses are lignin, a vast, complex molecule of three-way linked phenolic monomer units. Softwoods generally have the highest lignin content, while herbaceous plants such as grasses have the lowest [82], [83]. Lignocellulosic materials are resistant to lignin-induced chemical and biological degradation. The hydrolysis of cellulose and hemicelluloses to mono, di, and oligosaccharides is the limiting stage of the anaerobic degradation of lignocellulosic materials. To increase biomass conversion efficiency, the hydrolysis rate must be increased for anaerobic digestion.

6.2. Fruits and Vegetables Waste Digestion

Fruit and vegetable waste is well suited for energy recovery by anaerobic digestion because it has a high proportion of moisture (>80%), a high organic content (volatile solids >95% of total solids), and is rapidly biodegradable [84]. Waste from fruits and vegetables breaks down quickly and is frequently co-digested with other feedstocks.

7. Advantages of Biogas

The advantages of biogas can be summarized as follows:

1. **This is a renewable energy source:** The only way to deplete biogas is to stop all activities that generate waste. It is also a source of free energy.
2. **Non-polluting:** The nature of biogas is considered non-polluting.Since biogas production does not require oxygen, resources are conserved by not using any additional fuel. In addition, it reduces indoor air pollution of any kind and deforestation.
3. **It reduces landfills:** Since it also uses waste from landfills and landfills, it reduces oil and water pollution.
4. **Use cheaper technology:** Biogas applications are increasing due to advancements in technology using biogas. Besides being used to generate electricity, biogas can also be used for heating. Compressed natural gas (CNG), particularly biogas, is also used in automobiles.
5. **Many jobs are obtained:** Many job opportunities are created for installing biogas plants. These occupations are a blessing for people living in remote areas.
6. **Very little capital investment:** A biogas plant can be set up quickly and with little financial cost when built on a modest scale. Farmers can be self-sufficient by using the waste generated by their livestock to make biogas for the farm itself.
7. **It reduces the greenhouse effect:** The greenhouse effect is reduced thanks to the production of biogas from gases generated from landfills. This is a source of energy. Biogas is becoming more important as a resource because it is easy to make and recycles most of its organic or biodegradable waste.

The sketch in Fig. 9 shows the different utilization of biogas technology [85]:

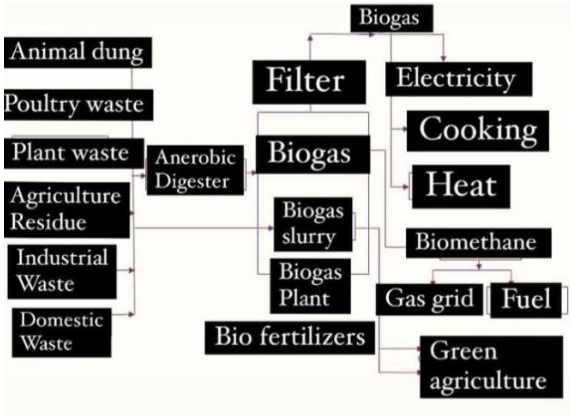

Figure 9. The utilization of biogas technology.

8. Disadvantages of Biogas

The disadvantages of biogas can be summarized as follows:

1. Few technological advancements: Because very few technical improvements are made or applied to streamline and reduce the cost of the process, the systems currently in use are inefficient. As a result, neither large-scale industrial biogas production nor its representation on the energy map is displayed [84]. Although investing in biogas production might help address some of the problems now being faced, most
2. It is made up of impurities: Although it has gone through many refining processes, biogas contains many contaminants. If this impurity-filled biogas is used as fuel after it is compressed, the metals in the engine could begin to corrode.
3. Large-scale biogas production is unattractive: Large-scale biogas utilization is unfeasible from a financial standpoint. It is also challenging to increase the efficiency of biogas systems.
4. Biogas is inherently unstable: Biogas becomes flammable when methane comes into contact with oxygen. This happens because biogas is unstable and, therefore, explosive [86]-[90].

9. Conclusion

Green, sustainable, and renewable energy are the future because fossil fuels will end. It is recognized that fossil fuel dependency, especially in foreign countries, will be decreased. Furthermore, fermented organic manure is obtained at the end of biogas production. The amount of biogas produced was monitored by measuring its volume and the average temperature daily. The digester temperature remained at 27 to 35°C through fermentation. Biogas generated from the first to the sixth day changed repeatedly and continued for two weeks. Biogas is highly recommended for use as our lack energy consumption and should be considered clean energy. Alternative energy sources must be used to ensure the smooth running of life. The use of biogas mitigates global warming while preventing dangerous infections. A lot of the energy and money generated from waste have no value. The construction of biogas plants will contribute to the creation of many different industries, reducing the unemployment rate. Waste is generated in enormous quantities; therefore, the biogas plant is available all around without any shortage.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Raghad Maher Wadi is a master's student, and Sroor Atallah Khalifa is the thesis supervisor.

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