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Review

A review of the effective factors involved in the production of biogas from biomass waste

Himan Khodkam*

Department of Biosystem Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

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*** Corresponding author**
h.khodkam@uma.ac.ir

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ABSTRACT

Every day, a lot of waste enters the environment from various sources, most of which is organic material. If organic waste is released or disposed of improperly, it can harm ecosystems for humans and animals. The best way to handle this waste is through anaerobic digestion technology. This method not only ensures proper disposal but also produces valuable materials, making it a win-win solution. The goal of this article is to review the effective factors involved in the production of biogas from biomass waste. Biogas is generated in four stages, and several key factors influence its production, including temperature, pH, carbon-to-nitrogen (C/N) ratio, residence time, mixing, and moisture levels. Each of these factors has an optimal point that needs to be reached for the highest production rates. By optimizing these conditions, production costs can be minimized, meeting most societal needs. To speed up and improve efficiency, different types of pretreatment can be used. These pretreatments often help break down lignin and silica, making the process more effective. Biological pretreatment is also an option, as it consumes less energy and is environmentally friendly. Additionally, zero iron nanoparticles have shown better potential than other types of nanoparticles. Research indicates that to achieve maximum biogas production, the coarse material should be reduced to small pieces, the feed concentration should be about 8% w/w, the C/N ratio should be around 25, the pH should be neutral, and the digester temperature should be set to mesophilic levels. However, it's important to note that the effectiveness of pretreatment can vary based on the materials used and the digestion conditions. Overall, efforts are focused on enhancing anaerobic digestion to maximize biogas output, which can help reduce fossil fuel consumption—the main contributor to global warming and climate change.

1. Introduction

The decomposition of organic matter by anaerobic bacteria in the absence of oxygen is called anaerobic digestion (AD), which results in biogas (Abbasi et al., 2012). This biogas is not only low-cost but also holds significant economic value due to the wide availability of raw materials used in its production (Kusmiyati et al., 2023). Biogas consists of several components, including water vapor (H_2O), nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4) (Show et al., 2023). Methane comprises 50-70% of biogas, while carbon dioxide accounts for 30-50% (Xia et al., 2016). Methane is particularly important because it is about 25 times more potent than carbon dioxide when it comes to contributing to climate change and global warming (Lilian et al., 2023).

When methane is used in a generator, it can create electricity, offering a renewable alternative to fossil fuels. In addition to producing biogas, AD also creates valuable byproducts like sludge and biofertilizers. These byproducts are rich in nutrients and carbon, especially in the form of humic and fulvic acids, making them beneficial for growing crops (Rasapoor et al., 2020). Using this biofertilizer can improve soil fertility and decrease the need for chemical pesticides (Møller et al., 2022).

AD, as a soil conditioner, has many advantages: it increases the potential for carbon fixation and minerals (nutrients) needed by plants, it can replace all inorganic fertilizers and significantly reduce the use of fertilizers from non-renewable sources, and it helps restore degraded and polluted areas and supports soil microbiological activities (Slepetiene et al. 2020 and Ibeto et al., 2020). Integration with other processes (such as composting, gasification, and pyrolysis) can reduce greenhouse gas emissions, increase the potential for renewable fuel production, and modify the characteristics of digested fuels, offering different properties and applications (Celletti et al. 2021; Wang and Lee 2021).

The AD process occurs in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, involving various interacting bacteria (Emmanuel et al., 2022). To achieve optimal efficiency, pre-treatment is necessary to homogenize the raw materials. The system design can be either continuous or batch-based, depending on specific conditions. In continuous systems, the dry matter content can be low (less than 15% of the total feedstock) or moderate (15 to 25% of the total feedstock). In contrast, in batch AD systems, dry matter can make up to 40% of the total feedstock (Costa et al., 2015). The steps of the AD process are shown in Figure 1.

Several pretreatment methods positively impact the AD, including chemical, mechanical, biological, and thermal processes. Recent experimental results indicate that these pretreatment methods can enhance the digestion of dairy manure, significantly increasing biogas yield by 2 to 3 times (Kim and Karthikeyan, 2021a; 2021b).

Temperature is a crucial factor in AD, as it influences both enzyme activity and methane yield (Appels et al., 2011) and affects the retention time of the process (Wirth et al., 2015). From both technical and economic perspectives, the mesophilic temperature range is considered the most suitable, as digesters operate more stably at this temperature (Elanur, 2020). Research shows that maximum methane production occurs under mesophilic conditions (Kovács et al., 2015). Thermophilic digestion helps produce methane faster, which means shorter processing times (Curry and Pillay, 2012). However, thermophilic conditions are more affected by changes in the environment than mesophilic conditions, so they need more careful management (Kim et al., 2006). The success of digestion also depends on the pH level (Jimenez et al., 2020). The best pH is close to neutral, ideally between 6.5 and 7.5. If the pH goes outside the range of 6 to 8, it can harm the bacteria that produce methane and lower biogas production (Muvhiiwa et al., 2016). The efficiency of biogas production is influenced by the composition of raw materials, the type of system used, and the AD process itself. AD can be conducted using either a single-stage or a two-stage method.

In the single-stage method, all degradation processes and methane production occur simultaneously in one stage. In contrast, the two-stage method separates these processes: the first stage focuses on the hydrolysis of organic compounds and the production of volatile fatty acids and hydrogen (H_2), while methane is produced in the second stage. This separation enhances hydrolysis, leading to improved methane yield (Ferreira, 2021; Rafieenia et al., 2017). Overall, AD converts approximately 35 to 40% of the total dry organic matter into methane (CH_4) and carbon dioxide (CO_2), while also reducing pathogenic microorganisms in the raw materials (Siegmeier et al., 2015).

The purpose of this article is to present the benefits of biogas technologies and the principles of implementing biogas production, including the optimization and monitoring of the AD process. Despite the challenges and limitations faced by biogas digester systems after installation and construction, efforts have been made to modify these systems to achieve the desired biogas yield through portable biogas digesters. By controlling the factors affecting microbial activity, the production rate can be maximized, leading to a reduction in the cost of produced gas and alleviating the energy shortages faced by society. Additionally, the fertilizer obtained from AD can be utilized in agriculture, thereby reducing the need for chemical fertilizers. While many articles have been published on biogas, none have comprehensively examined the factors influencing biogas production and the effects of the resulting products on human life.

2. Dry and wet anaerobic digestion

Factors such as the operating environment, retention time, type of raw material, and available equipment play a role in choosing the digestion method (Paritosh et al., 2017). There are two ways to remove organic matter: aerobic digestion and aAD. What is produced in AD includes methane, carbon dioxide, and trace amounts of other gases, the percentage of which may vary depending on the type, properties, and amount of raw material (Alam et al., 2022).

AD can be conducted in two forms: high solid AD (HS-AD) and liquid AD (L-AD), depending on specific conditions. In solid digestion, the dry matter content exceeds 15%, while in liquid digestion, it is less than 10%. Liquid digestion yields significantly more methane than solid digestion (Zhang et al., 2014), with methane production being 13.6% higher in the liquid state. This increase can be attributed to the optimal carbon-to-nitrogen (C/N) ratio present in liquid conditions. However, HS-AD offers several advantages over L-AD, including smaller reactor dimensions, lower costs, reduced nutrient losses, decreased water consumption and lower maintenance costs (Sun et al., 2014).
AD can also be performed using either a single-stage or a two-stage approach. In the single-stage method, all degradation and methane production processes occur simultaneously. In contrast, the two-stage method separates these processes: the first stage involves the hydrolysis of organic compounds, volatile fatty acids, and hydrogen (H_2) production, while methane is produced in the second stage. The hydrolysis process is more efficient under both aerobic and anaerobic conditions in the two-stage mode, which enhances methane production yield (Rafieenia et al., 2017). In Table 1, dry and wet AD are compared based on several important parameters.

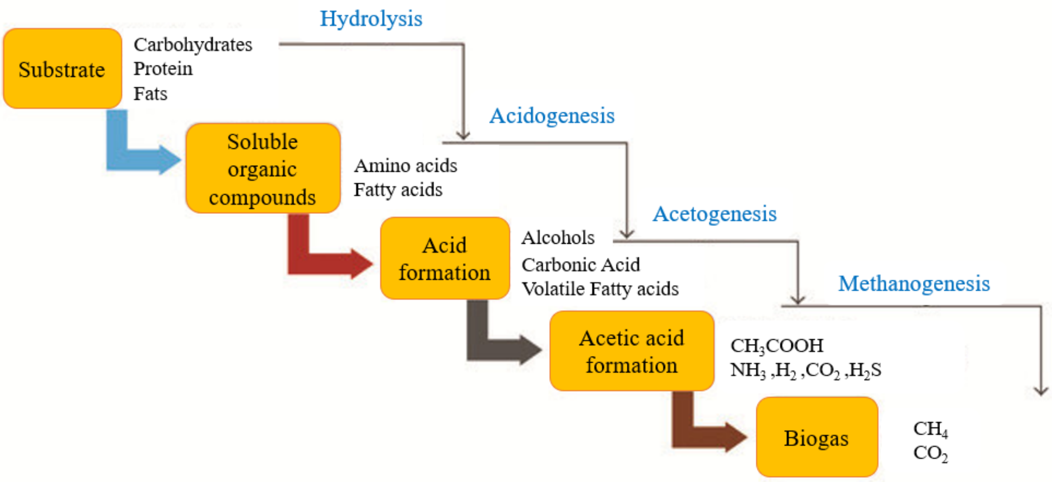

Figure 1. Anaerobic digestion process

Table 1. compares dry and wet anaerobic digestion

Parameter	HS-AD	L-AD
Required space according to reactor dimensions	Due to its small size, the reactor requires little space.	Due to the large size of the reactor, it requires more space.
Maintenance cost	Requires little expense.	It has a high maintenance cost.
Nutrient losses	Low	A lot
Water consumption	Low	A lot
Methane production rate	Low	A lot
The initial cost of the loaded material	A lot	Low

3. Ideal conditions for the growth of bacteria and enzymes

Bacteria play a crucial role in the conversion of organic matter into biogas. To accelerate this process and increase biogas production, it is essential to provide optimal conditions. The critical variables affecting the performance of a biogas plant include temperature, pH, C/N ratio, retention time, agitation, moisture content, particle size, microbial activity concentration, hydrolysis rate, and the degree of biomass degradation (Dioha et al., 2013). Below are important points regarding each parameter:

3.1. Temperature

Temperature is one of the most critical parameters in AD, as it influences both enzyme activity and methane yield (Appels et al., 2011). A sudden decrease in temperature of more than 2 °C can significantly impact the amount of gas produced (Mulat and Feilberg, 2015). Rapid fluctuations in temperature disrupt bacterial activity (Rea, 2014). At temperatures below 30 °C, the digester environment becomes acidic, while at temperatures above 60 °C, the activity of digesting microorganisms decreases and may eventually cease. From both technical and economic perspectives, the most suitable temperature range is mesophilic, where the digester operates more stably (Elanur, 2020).

Based on the research conducted, it can be concluded that the optimal temperature for stability and biogas production is the mesophilic range. This temperature is less sensitive to fluctuations and yields satisfactory amounts of biogas. Ensuring the continued viability of microorganisms is essential for biogas production in any digester, as these organisms are responsible for the decomposition and breakdown of organic matter. At mesophilic temperatures, the highest levels of decomposition occur. In Table 2, digesters are classified according to their temperature ranges and characteristics.

3.2. pH and volatile fatty acids

The pH level should be kept close to neutral, ideally between 6.5 and 7.5. If the pH goes outside the range of 6 to 8, it can harm the bacteria that produce methane and reduce biogas production (Muvhiiwa et al., 2016). This can lead to more acid buildup (Rea, 2014). When the pH drops to 6.5 or lower, it significantly slows down microbial activity (Wagner et al., 2013) and makes it harder to break down organic matter (Zhang and Jahng, 2012). If the pH falls below 6, the methane content in biogas can drop below 50%, making it non-flammable (Rao et al., 2010). At a pH below 5.5, bacterial activity becomes inactive (Sharma, 2002).

Volatile fatty acids are essential for AD because they help determine the pH level (Zhan et al., 2023). By managing acid-producing bacteria and pH levels, we can control the population of bacteria (Horiuchi et al., 2002; Fang and Liu, 2002). Research shows that pH is crucial for the survival of microorganisms, especially methanogens, as it directly affects their growth and activity. These microorganisms are most active at a neutral pH of 7. If the pH strays from this ideal level, it can harm their ability to break down organic matter, leading to decreased biogas production. If these unfavorable conditions continue, biogas production could stop completely.

3.3. C/N ratio

The C/N ratio significantly impacts the performance of AD (Karthikeyan and Visvanathan, 2012). For stable long-term AD, a balanced C/N ratio is essential (Zhan et al., 2023). Mixing carbon-rich waste substrates with nitrogen-rich materials (such as food waste and Chicken manure) achieves the optimal C/N ratio for the AD of mixed wastes (Korai and Li, 2020). The optimal C/N ratio for AD has been reported to be between 21 and 31 (Zhou et al., 2022). By maintaining the C/N ratio within the range of 25 to 30, the solution can remain neutral (pH = 7), allowing for the production of biogas with up to 70% methane (Rao et al., 2010).

Researchers have suggested that a C/N ratio lower than the optimal value can also be effective for biogas production (Wagner et al., 2013). If the carbon content is below the optimum, excess nitrogen accumulates in the digester, leading to bacterial toxicity and the death of many bacteria. Conversely, if nitrogen levels are insufficient, microorganisms may struggle to survive due to a lack of food sources.

In a study involving three organic materials (dairy, chicken manure, and wheat straw), maximum methane production was achieved at a C/N ratio of 27.2, with a stable pH and low cumulative ammonia concentration (Zhang et al., 2012). The lower optimal C/N ratio may be attributed to the positive effect of nitrogen on the mobility and activity of microorganisms. Research indicates there is a specific range for the C/N ratio, and exceeding this range may yield negative results. Overall, while excess nitrogen can have a beneficial role to a certain extent, surpassing this threshold can lead to adverse effects.

3.4. Retention time

Retention time is directly related to the amount of biogas produced. Methane yield increases with longer retention times and higher organic matter content. In a biogas production system, the typical retention time ranges from 30 to 50 days (Diltz and Pullammanappallil, 2013). Over time, while biogas production may initially increase, the rate of production eventually declines. As retention time extends, the overall output may not justify the energy and time invested. Eventually, the downward trend in biogas production approaches zero, with complete cessation occurring at varying times depending on the type of feedstock used.

3.5. Mixing

Mixing materials in the digester helps distribute nutrients evenly throughout the system (Zabaleta and Rodic, 2015). This process prevents the settling of loaded materials, equalizes the temperature within the digester, reduces foaming, and facilitates the escape of biogas from the materials (Hosseini and Wahid, 2014). Depending on the type of agitator used, the energy required for mixing can be reduced by up to 70% (Lemmer et al., 2013). To enhance methane yield in biogas production, some of the material exiting the digester is recycled back to the inlet (Meng et al., 2022). Research indicates that increasing the agitation speed decreases mixing time (Melton et al., 2002). Paddle agitators are particularly effective for very viscous fluids and are commonly used to prevent the formation of floating layers. In terms of energy consumption, slow-speed paddle agitators are more efficient than high-speed floating agitators (Annas et al., 2022).

Table 2. Classification of digesters in terms of temperature and their characteristics

Medium temperature range	characteristics
Psychrophilic 15-18 °C	High probability of environmental acidification, Low biogas production, Long retention time
Mesophilic 28-33 °C	The highest biogas production rate compatible with the conditions of microorganisms.
Thermophilic 50-60 C	The possibility of microorganisms being destroyed by heat, sensitive to temperature changes, Low water requirement, rapid biogas extraction, Higher percentage of methane produced compared to the other two groups, and Short retention time.

3.6. Total solids content

Excess or deficiency of moisture has a direct effect on the amount of gas produced (Lohani et al., 2013). Previous studies have reported that the best concentration for AD in a biogas plant is 7-9% total solids (TS). Increasing the TS increases the biogas yield by 2-8%, while the biogas yield decreases at TS = 10% w/w. A 1.5-fold increase in yield was observed at TS = 8% w/w compared to TS = 5% w/w, because at higher TS, VFA increased and methane yield decreased slightly (Curry and Pillay, 2012). Concentration is an important factor in AD, and just as increasing TS increases reactor efficiency, decreasing TS can also decrease the yield due to dilution and nutrient deficiency of microorganisms.

3.7. Ammonia

Ammonia, a product of the biological decomposition of organic matter, typically exists in two forms: ammonium (NH^{4+}) and free ammonia (NH_3) (Whelan et al., 2010). While ammonia is essential for bacterial growth, high concentrations can be toxic to these microorganisms (Kim and Oh, 2011). Ammonia plays a critical role in balancing the C/N ratio and can enhance AD performance by neutralizing VFAs produced during the digestion process (Wang et al., 2012). However, elevated ammonia concentrations can lead to reduced biogas production, digestion failure, and the release of ammonia into the effluent (Park et al., 2010). A small amount of ammonia is necessary for the survival of microorganisms, but exceeding a certain threshold can halt the digestion process.

3.8. Long-chain fatty acids

Biodegradation is considered the rate-limiting step in AD. This limitation is primarily attributed to the initial concentration of long-chain fatty acids (LCFAs), with higher concentrations often leading to the failure of AD processes (Oh and Martin, 2010). The inhibitory effect of saturated fatty acids on the system intensifies with an increase in the number of double bonds and chain length (Lalman and Bagley, 2002). Food waste serves as a rich source of fat, typically containing fat concentrations of approximately 5 g/L (Kim et al., 2010).

4. Methods for biomass pretreatment in anaerobic digestion

After looking at the important factors, pretreatment is used to improve the efficiency of the AD process. This method speeds up the breakdown of organic matter, leading to faster biogas production (Jain et al., 2015). When lignocellulose is treated, it helps break down cellulose and hemicellulose, turning complex carbohydrates into simpler sugars that can be fermented (Zheng et al., 2014). Researchers have been studying different types of pretreatment to increase biogas production rates for many years (Li et al., 2013). Studies show that pretreatment can significantly boost methane production from lignocellulosic biomass and shorten digestion time (Li et al., 2020).

Recent experimental results have shown that pretreatment methods can enhance the digestion process of dairy manure and significantly increase the biogas yield (2-3 times) (Kim and Karthikeyan, 2021a; 2021b). Pretreatments are divided into three categories: physical (mainly mechanical, thermal, and ultrasonic), chemical (mainly acidic and alkaline), and biological pretreatment (mainly enzymes, fungal and microbial consortium pretreatment, micro-aerobic, and ensiling). The results of the pretreatments are summarized in Table 3.

5. Analysis of technical, economic, and environmental impacts of different types of pretreatments

Different pretreatment methods can be used for various types of biomass, but cost is a major factor in biogas production. The best pretreatment method is one that is affordable and has low operating costs. The main challenge is finding a specific pretreatment that increases biogas yields the most. Mechanical pretreatment methods often require a lot of energy and can lead to high operating and maintenance costs, especially on a large scale, which raises the overall cost of biogas production. Therefore, combining different pretreatment methods is usually more cost-effective than using just one method to boost biogas production.

5.1. Mechanical pretreatment

To achieve better results, mechanical pretreatment is usually done before chemical and microbial pretreatment (Cai et al., 2021). This process involves crushing materials, which improves digestion by increasing the contact surface area. For example, one study found a 43% increase in methane production when the particle size was reduced from 2 mm to 0.125 mm (Lindmark et al., 2012). Another study showed that the consumption rate doubled when the average particle size decreased from 2.14 mm to 1.02 mm (Zhang et al., 2014). This suggests that smaller particle sizes can improve the biodegradability of lignocellulosic biomass (LBs) (Kang et al., 2019). However, excessive mechanical pretreatment—especially if the particle size is reduced too much—can hinder methane production. This is due to the buildup of volatile fatty acids (VFAs), which can negatively affect digestion performance and lead to lower net energy production (Ferreira et al., 2014; Lindmark et al., 2012).

Shredding is a cost-effective and convenient method that is often preferred, as it significantly boosts biogas production efficiency. It's important to note that the effectiveness of shredding depends on the type of organic matter, making it hard to define a specific size value. Generally, though, reducing the size of the material tends to improve biogas production efficiency.

5.2.Chemical pretreatments

These pretreatments include alkaline and acidic methods. The main goal of alkaline pretreatment is to increase porosity through hydrolysis, which helps microorganisms digest the material more effectively (Yu et al., 2019). Common chemical methods involve adding substances like ammonia fiber explosion, CO_2 explosion, and acid-alkali separation (Kim and Han, 2012).

After using a 10% CaO pretreatment, researchers found an 11.99% increase in methane production (Solé-Bundó et al., 2017). Bases such as sodium hydroxide (NaOH), potassium hydroxide (KOH), calcium hydroxide ($Ca(OH)_2$), and ammonium hydroxide (NH_4OH) improve the porosity of the material and reduce the polymerization of lignin (Sundberg, 2010).

Table 3. Pretreatments and their characteristics

Types of pretreatments		characteristics
Mechanical		By converting into smaller pieces, degradability increases, resulting in increased biogas production efficiency. Excessive reduction reduces digester performance.
Alkaline	Chemical	NaOH is the most widely used type.
Acidic		They are less effective than alkaline.
Thermal		It improves performance but is not economically viable.
Biological		It includes two types, enzymatic and microbial, and both increase performance. It is popular due to its low energy consumption and environmental friendliness.
Integrated		It is more efficient than physical pretreatment or chemical pretreatment.
Alkaline thermal		Mixed growth conditions are more difficult to control, requiring in some cases much longer periods of time than physical or chemical pretreatment.

This process dissolves lignin, making hemicellulose easier for microbes to break down, leading to higher biogas production rates (Sundberg, 2010; Vu et al., 2020). Among these methods, alkaline pretreatment with sodium hydroxide (NaOH) is one of the most commonly used techniques for treating lignocellulosic biomass (Saratale and Oh, 2015). Xu et al. reported a significant increase in biogas yield of up to 57% with 8% NaOH pretreatment at 175 °C (Zhou et al., 2016). Another study showed a remarkable 111.6% increase in methane production from wheat straw pretreated with 4% NaOH at 37 °C for 120 h (Karami et al., 2022).

In contrast, acidic pretreatment generally exhibits lower performance compared to alkaline pretreatment, even when using the same molar concentration of acid. A study comparing the effects of H_2SO_4, H_2O_2, HCl, and CH_3COOH pretreatments on rice straw revealed that hydrogen peroxide (H_2O_2) pretreatment had the highest biogas production potential. However, it is often observed that organic acid pretreatment at low concentrations may not yield satisfactory results in terms of biogas production. Conversely, high concentrations of organic acid pretreatment can result in significant dry matter loss, which can be detrimental to AD processes (Song et al., 2014). The extent of pretreatment required depends on the type of organic material, and a specific amount cannot be universally determined.

5.3. Thermal pretreatments

Thermal treatment is a process that utilizes heat to break down large molecules, aiding in the decomposition of compounds and increasing the amount of dissolved organic matter. This process also involves microbes that convert organic matter into biomethane (Wid and Raudin, 2023). Recent studies indicate that combining thermal pretreatment with AD may not be cost-effective (de Oliveira et al., 2022). However, profitability can be achieved by focusing on improving energy efficiency, enhancing operational capacity, and adopting new technologies (Kim et al., 2022). These strategies can enhance the economic viability of AD when used alongside thermal pretreatment.

Various methods for heating substrates, such as autoclaves, hot water baths, ovens, and microwaves, are employed for thermal treatment (Kainthola et al., 2019). All thermal pretreatments effectively assist in dissolving lignocellulosic biomass (LBs) (Cai et al., 2021). Overall, research suggests that pretreatment is generally not a cost-effective solution.

5.4. Biological pretreatments

Biological pretreatment methods can improve methane production by changing the structure of biomass and using co-digestion techniques (Karami et al., 2022). This method benefits from low energy use (Neshat et al., 2017) and is environment-friendly (Kavitha et al., 2022), making it a promising choice (Cai et al., 2021). Overall, biological pretreatment helps increase biogas production and is more environmentally friendly than chemical methods. While it works more slowly and doesn't cause damage, its overall effects might not be as strong as other pretreatment methods.

6. Application of nanoparticles in biogas production

Many nanoparticles are added to the process as enhancers. Iron, as an electron donor, is able to accelerate the hydrolysis process in the AD process (Karri et al., 2005). Iron nanoparticles are unstable and slowly dissolve iron ions and increase the activity of methanogenic microorganisms (Hao et al., 2017). The addition of iron by stimulating and stabilizing AD (affecting the conditions of methanogenic microorganisms through controlling pH, volatile fatty acid content, and ammonia nitrogen concentration) leads to improved biogas production performance (Suanon et al., 2017). The addition of iron nanoparticles increased biogas production up to the first 48 h, but high concentrations gradually led to a decrease in biogas production by poisoning the bacteria (He et al., 2008). The results published in the articles showed that iron nanoparticles in small amounts by controlling the pH (keeping it in the neutral range) increase digestive performance. However, large amounts lead to the poisoning of methanogenic microorganisms.

Metals, as nutrients, play an important role in the performance and stability of agricultural biodigestion (Rasouli et al., 2015). Adding metal elements to AD can significantly improve its performance. In addition to nutrients (N, O, H, C), anaerobic bacteria require metal elements including metal ions (Al, Ca, Mg, K, Na) and heavy ions (Ni, Zn, Cu, Co, Cr) (Jin et al., 1998). In addition, metal elements such as Co, Cu, Fe, Mo, and Ni can play an important role in stimulating and stabilizing AD of organic waste at low concentrations (Roussel, J. 2013).

Adding heavy metals Ni^{2+}, Zn^{2+}, and Cu^{2+} improves the performance of the digester, and the best biogas performance is achieved with the addition of Ni^{2+} at a rate of 100 ppm (Okeh et al., 2014). When the concentration of light and heavy metals is too high, the system is inhibited (Abd Elnabi et al., 2023). In a study, the effect of four types of metal oxide nanoparticles (TiO_2, Al_2O_3, SiO_2, ZnO) on AD was investigated and only ZnO had an inhibitory effect on methane production. However, at low concentrations, it had no effects (Mu et al., 2011). Increasing the iron and zinc oxide nanoparticles and reducing the cobalt oxide nanoparticles have a positive effect on the methane yield produced (Khaledian et al., 2021). Fe_3O_4 nanoparticles were used for the AD of municipal waste and the results showed that 75 g/l was the optimal amount and using more than this amount reduced methane production (Otero-González et al., 2014).

7. Conclusion

Pollution from fossil fuels, which currently supply most of the world's energy, is a major reason for the move towards renewable energy sources. Biogas comes from various readily available sources around the world and its type depends on the location and living conditions. There are two main methods for producing biogas. Several factors affect biogas production, including temperature, the type of reactor, the concentration of inputs, the kind of feedstock, and mixing. To improve production rates, materials can be added as a pretreatment, which often helps. However, the cost-effectiveness of these pretreatments needs careful consideration. The main goal is to lower the final cost of the biogas produced by creating good conditions for bacteria to thrive. Changes in temperature can disrupt bacterial activity and even stop it altogether. Research shows that moderate temperatures are best for stable digestion and maximum biogas production. The speed of digestion decreases with longer mixing times, making mixing an important factor in avoiding sediment buildup.

The C/N ratio is typically around 25 in most studies. While a small amount of ammonia is essential for bacterial survival, exceeding certain limits can lead to digester toxicity and halt production. It is important to ensure that the concentration and size of the input materials are neither too low nor too high, as this can disrupt the digestion process. Economic efficiency is a critical limiting factor, with a specific range; production outside this range lacks economic viability. Accelerating and enhancing the production rate—its primary goal—can be achieved through pretreatment. Pretreatment is the most common method for improving the efficiency of AD of LBs.

AD is an established and straightforward technology that converts complex organic matter (biomass) into simpler forms. This process leads to the reduction or elimination of odors, destruction of pathogens, and breakdown of carbon. The resulting biogas can be burned to produce energy, used directly for cooking, or purified for further applications. The materials remaining after digestion are rich in nutrients and carbon. This process concentrates available nutrients and produces stable carbon that is easily absorbed by the soil. It enhances soil quality by increasing organic matter and microbial activity, acting as an effective soil conditioner. The use and effects of these residual products depend on the composition of the incoming raw materials and the technology employed. They can increase the ratio of humic acids to fulvic acids, thereby boosting soil organic matter. The extent of this increase varies based on the type of raw material used.

The residues, both solid and liquid, can be applied separately or in combination in the soil, with studies indicating that combined use is more effective. This application improves soil quality, restores degraded areas, and helps remove heavy metals. Additionally, integrating process residues with other methods such as pyrolysis, gasification, and composting enhances efficiency, stability, and carbon storage capacity in the soil while also mitigating issues related to nutrient leaching and environmental pollution.

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