IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

MEDICAL WASTE TO BIOGAS: A SUSTAINABLE SOLUTION FOR WASTE MANAGEMENT AND RENEWABLE ENERGY PRODUCTION

[1]Sabir Hussain, [2]Rajesh Jesudasan, [3]Kamthong T, [4]Priyakshi Chutia, [5]Abhijit Nath

[1]Assistant Professor at The Assam Kaziranga University, [2] Professors at The Assam Kaziranga University, [3]Assistant Professors at The Assam Kaziranga University, [4]Assistant Professors at The Assam Kaziranga University, [5]Assistant Professors at The Assam Kaziranga University

[1]School of Pharmacy,
[1]The Assam Kaziranga University, Jorhat, India

Abstract: The proper management of medical waste is crucial to ensure the safety and well-being of both healthcare workers and the general public. Traditional methods of medical waste disposal, such as incineration and landfilling, have significant environmental and health risks. The creation of biogas from medical waste provides a sustainable and eco-friendly option for waste management and energy demands.

Biogas production from medical waste offers several benefits. Firstly, it provides a renewable source of energy, reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Second, it makes it easier to handle waste properly, reducing the hazards that medical waste poses to the environment and human health. A further way that biogas production may support the circular economy is by turning garbage into a useful resource. However, overcoming a number of obstacles is necessary for efficient biogas generation from medical waste. These include managing any possible pollutants or hazardous materials that may be present in medical waste, as well as the appropriate segregation and collection of medical waste. To further encourage and assist the development of biogas generation from medical waste, legislative frameworks, and regulatory measures are crucial. Recent improvements in biogas production technology, such as the use of sophisticated anaerobic digestion systems and the integration of pre-treatment techniques, have shown encouraging results in increasing the efficiency and dependability of the process. Additionally, cutting-edge methods have been investigated to improve biogas output and quality, such as co-digestion with other organic waste streams or the utilization of microbial consortia.

***IndexTerms* - Biogas; Medical waste; Energy generation; Pathogen inactivation**

INTRODUCTION

Due to the potential threats to human health and the environment from inappropriate disposal, managing medical waste is a crucial issue on a global scale. The creation of biogas from medical waste offers a long-term and ecologically responsible answer to this issue. Anaerobic digestion of organic waste materials, particularly medical waste, can produce biogas, a combination of methane and carbon dioxide. This procedure contributes to a circular economy by producing renewable energy in addition to lowering the amount of garbage.

There has been an increase in interest in using medical waste to produce biogas in recent years. Safe disposal of medical waste, which comprises a variety of contagious and non-infectious waste produced by healthcare institutions, is a serious concern. Medical waste handling errors can result in the discharge of dangerous chemicals, the spread of infections, and environmental contamination. Therefore, it is crucial to identify sustainable ways to handle medical waste.

The breakdown of organic waste by microorganisms in the absence of oxygen is a component of the anaerobic digestion process for the generation of biogas. As a byproduct of this process, biogas is created, which may be utilized as a sustainable energy source for heating, power production, and other purposes. The nutrition loop is closed by the digesting process' additional production of nutrient-rich digestate, which may be utilized as a biofertilizer.

The viability and possibility of using medical waste for biogas generation have been examined in several research. For instance, Smith et al (2018) study looked at the anaerobic digestion of medical waste in a pilot-scale digester and showed how it may produce biogas. A different investigation by Gupta et al. (2020) looked at the dynamics of the microbial population during the anaerobic digestion of medical waste and pinpointed the major variables affecting biogas generation.

This study intends to further investigate the potential of medical waste to produce biogas and to solve the difficulties in utilizing it effectively. The study will look into the makeup and features of medical waste, measure the effectiveness of various anaerobic digestion methods, gauge the quantity and quality of biogas produced, and assess the process's feasibility from an economic and environmental standpoint. The results of this study will help the healthcare industry create environmentally friendly waste management procedures, encourage the production of renewable energy, and lessen the negative effects of medical waste on the environment. (Smith et al.,2018, Gupta et al.,2020)

1.1. Medical Waste and its environmental impact

Hospitals, clinics, and laboratories that provide healthcare produce a significant amount of medical waste. It is made up of a variety of substances, including sharps, infectious, pharmaceutical, and chemical waste, which, if improperly managed, represent serious threats to the environment and public health. Medical waste may pollute waterways, contaminate land, release hazardous gases, and transmit infectious illnesses if it is not properly disposed of and treated. The purpose of this article is to examine how medical waste affects the environment and to emphasize the possibility of biogas production as a long-term waste management strategy.

1.1.1. Effects of Medical Waste on the Environment

1.1.1.1. Water pollution:

Pharmaceuticals and medical waste, especially infectious waste, should never be disposed of improperly since they might pollute water supplies. Medical waste can leach chemicals and germs, contaminating groundwater and surface water, when it is disposed of in landfills or bodies of water. The health of people, as well as aquatic ecosystems, may be negatively impacted by this pollution.

1.1.1.2. Air Pollution

Incineration, a frequent technique for handling medical waste, increases air pollution. By burning medical waste, harmful chemicals including dioxins, furans, and mercury are released into the environment, which can have a negative impact on the local community's air quality and long-term health.

1.1.1.3. Land Contamination

Poorly handled medical waste can contaminate the land, endangering the health of people, animals, and plants. Hazardous materials can leak into the soil if medical waste is not adequately separated or disposed of in designated facilities, potentially entering the food chain and resulting in long-lasting ecological harm.

1.1.1.4. Greenhouse Gas Emissions

Methane, a strong greenhouse gas, is produced when medical waste is dumped. Methane is produced during the anaerobic breakdown of organic compounds, particularly medical waste. Methane has a far larger potential for global warming than carbon dioxide, which means that it plays a role in climate change. Methane emissions can be reduced by avoiding landfills and utilizing medical waste instead to make biogas.

A sustainable waste management approach with the potential to improve the environment is provided by the generation of biogas from medical waste. Medical waste may be converted into biogas via anaerobic digestion, a technique that consumes organic material without oxygen. Methane and carbon dioxide make up the majority of this biogas, which may be utilized to generate electricity, decreasing the need for fossil fuels and lowering greenhouse gas emissions.

If medical waste is not adequately managed, it poses a serious hazard to the environment. Some of the negative effects linked to insufficient medical waste management include greenhouse gas emissions, water pollution, air pollution, land contamination, and others. However, medical waste may be successfully and sustainably handled by introducing biogas production through anaerobic digestion, minimising environmental impact and supporting the creation of renewable energy. (Ismail et al.,2021, World Health Organization 2021)

1.2. Need for sustainable medical waste management

Due to its potential effects on the environment and public health, medical waste management is a crucial concern in healthcare institutions. Infectious disease transmission, water body pollution, air and soil contamination, and incorrect medical waste management are all risks. The amount of medical waste produced is rising due to the expanding worldwide population and healthcare activities, necessitating efficient and long-term management techniques. This essay intends to draw attention to the need of environmentally sound medical waste management and its potential role in biogas generation.

1.2.1. Environmental Effects

Medical waste contains potentially harmful items including chemicals, medications, and infectious agents that, if improperly treated, can damage the environment. Poor waste management techniques, such as open burning and landfilling, emit harmful chemicals into the air, pollute groundwater, and increase the production of greenhouse gases. (Smith et al.,2020)

1.2.2. Risks to Public Health

Improper management and disposal of medical waste pose serious threats to the general public's health. Injury, illness, and exposure to hazardous materials are risks that affect everyone in the community, including waste handlers, healthcare personnel, and the general public. A significant worry is the potential for infectious illnesses like hepatitis and HIV to spread through tainted medical waste. (World Health Organization et al.,2019)

1.2.3. Regulatory Compliance

To guarantee the appropriate treatment of medical waste, governments, and regulatory agencies have put strict norms and laws into place. To avoid legal responsibilities, fines, and harm to the reputation of healthcare institutions, compliance with these standards is essential. Meeting regulatory criteria requires the use of sustainable waste management techniques. (U.S. Environmental Protection Agency 2021)

1.2.4. Resource conservation

Effective medical waste management makes it possible to recover and recycle priceless resources. Plastics, metals, and glass are just a few of the components of medical waste that may be recycled, lowering the need for new resources. The organic portion of medical waste may also be used to create biogas, a green energy source. (Behera & Shuvendu, 2020)

It is clear that sustainable medical waste management is required to reduce the threats incorrect disposal practices have to the environment and human health. Healthcare institutions may reduce their negative environmental effect, safeguard the public's health, adhere to legislation, and maximize resource recovery by using sustainable waste management practices. The creation of biogas from medical waste appears to be a potential method for managing trash and producing sustainable energy.

1.2. Biogas Production as a Sustainable Solution

Medical waste creation presents serious environmental and public health problems. Traditional disposal techniques, such as incineration and landfilling, increase greenhouse gas emissions, air pollution, and the risk of the spread of infectious illnesses. Investigating sustainable options for managing medical waste is essential as the global healthcare sector grows. By using the energy potential of medical waste while minimizing its detrimental environmental effects, biogas generation offers a feasible option.

Anaerobic digestion of organic waste, particularly medical waste, is the process used to create biogas, which is a combination of methane and carbon dioxide. This technique not only prevents garbage from going to landfills, but it also produces renewable energy that can be used in a variety of ways. By converting biogas into power, heat, or even biofuels, it is possible to lessen reliance on fossil fuels and reduce greenhouse gas emissions.

Medical waste has a high energy content that makes it excellent for biogas generation. It includes a variety of organic components, including blood-soaked bandages, outdated medications, and anatomical tissues. Anaerobic digestion of medical waste has the potential to produce sustainable energy since studies have shown its viability as a feedstock. For instance, Smith et al.'s (2018) study looked at the anaerobic co-digestion of organic waste streams, including medical waste, and found considerable biogas production. Similar to this, Johnson et al. (2021) looked into the feasibility of using medical waste as a stand-alone feedstock and discovered that it may be used to produce biogas.

Beyond just providing energy, the creation of biogas from medical waste also benefits the environment. By reducing the amount of trash, the anaerobic digestion process helps to lessen the requirement for landfill space. Additionally, it helps eliminate dangerous germs, stopping their spread into the environment. This factor is especially important when dealing with medical waste since it frequently contains infectious organisms that might spread illnesses. The danger of disease transmission can be considerably decreased by successfully processing medical waste through the generation of biogas.

The creation of biogas from medical waste offers a long-term answer to the urgent problems linked to the disposal of waste from the healthcare industry. By keeping garbage out of landfills and utilizing renewable energy sources, it provides a double advantage. Medical institutions may lessen their environmental impact and help the transition to a more sustainable energy future by installing effective anaerobic digestion systems. To optimize the biogas generation process from medical waste and assure its widespread use in healthcare waste management policies, more research and development in this area are very necessary. (Johnson et al.,2020, Smith et al.,2018)

2. Types of Medical Waste Suitable for Biogas Production

2.1 Infectious Waste:

Infectious waste is garbage that has the ability to transmit diseases or contains germs. Used gloves, used clothing, used masks, contaminated bandages, used cultures, lab waste, and other items that have come into contact with infectious microorganisms are examples of such items.

Because it successfully eliminates pathogens and reduces the amount of trash, the production of biogas can be a good approach for treating infectious waste. Anaerobic digestion is used to create biogas because it breaks down organic material without oxygen. This process creates biogas, which is mostly composed of methane and carbon dioxide and may be used as a sustainable energy source.

High temperatures and certain conditions during the anaerobic digestion process remove or inactivate germs found in the infectious waste. Microorganisms break down the organic waste components, creating biogas as a by-product. The resultant digestate may then go through additional processing or may be safely discarded as non-infectious trash.

It's important to note that infectious waste should be handled and processed following appropriate safety protocols and regulations to ensure the protection of workers, the environment, and public health. (World Health Organization 2014)

2.2 Pharmaceutical Waste

Pharmaceutical waste includes unneeded, out-of-date, or tainted pharmaceuticals, medicines, and goods. To avoid environmental pollution and potential harm to human health, it is essential to handle pharmaceutical waste properly.

Despite the fact that pharmaceutical waste is often not suited for direct biogas generation, certain of its organic components can be used in the biogas production process. Anaerobic digestion may be used to break down organic chemicals included in some pharmaceutical waste, which helps to create biogas.

However, it is crucial to remember that suitable disposal techniques that reduce their negative effects on the environment and guard against possible injury should be the main priority when handling pharmaceutical waste. Pharmaceutical waste may need special treatment, such as burning or chemical neutralization, in accordance with local laws and regulations.

It is essential to adhere to the proper procedures and laws for disposing of pharmaceutical waste, taking into account the particular specifications and guidelines offered by regional authorities and environmental organizations. (World Health Organization 2014)

2.3. Chemical Waste

Hazardous compounds such as solvents, disinfectants, lab reagents, and heavy metals are only a few examples of chemical waste in the medical industry. To avoid environmental pollution and safeguard public health, chemical waste management must be done properly.

Biogas production is generally not suitable for directly treating chemical waste due to the potential risks and complications associated with the anaerobic digestion process. Many chemicals present in medical waste can interfere with or inhibit the digestion process, reducing its effectiveness or posing risks to the microorganisms involved.

It is crucial to treat and dispose of chemical waste using procedures that are suitable for managing hazardous waste. These techniques can involve chemical processing, burning, or dedicated disposal sites outfitted to deal with dangerous materials.

It is essential to follow regional laws and directives issued by environmental organizations and waste management authorities in order to ensure correct handling of chemical waste. To reduce the environmental effect and safeguard public health, these rules frequently specify particular methods for the collection, storage, transportation, and disposal of chemical waste. (World Health Organization 2014)

3. Anaerobic Digestion Process

3.1 Basic Principles of Anaerobic Digestion

Anaerobic degradation, often known as digestion, is a biological process where organic carbon is transformed to its most oxidized state (CO2) and its most reduced state (CH4) by repeated oxidations and reductions. In the absence of oxygen, a vast variety of microorganisms catalyze the reaction. Carbon dioxide and methane are the process' primary byproducts, but a small amount of nitrogen, hydrogen, ammonia, and hydrogen sulfide are also produced (typically less than 1% of the total gas volume). Biogas is the word for both the mixture of gaseous products and the anaerobic degradation process. Minerals and salts that are organically bound are liberated into their soluble inorganic forms as a result of the elimination of carbon. The production of biogas is a natural process that takes place in many anaerobic settings. These settings include mud, sewage effluent, fresh and marine sediment, etc.The following two factors account for most of the interest in the procedure: - The creation of biogas, which can be used to generate various types of energy (heat and electricity) or be processed for automobile fuel.

- A high degree of reduction of organic matter is achieved with a modest increase - in comparison to the aerobic process - in the bacterial biomass. (Angelidaki et al.2003)

3.2. Steps Involved in Anaerobic Digestion of Medical Waste

Multiple microbial species collaborate to break down complex organic matter into byproducts like methane, carbon dioxide, hydrogen sulfide, water, and ammonia, as well as new bacterial cells, in an environment known as anaerobic digestion.

Despite the fact that anaerobic digestion is often thought of as a two-phase process, it may really be divided into numerous metabolic pathways with the help of various microbial species, each of which has a particular physiological activity, as illustrated in Fig. 1 and explained in the following:

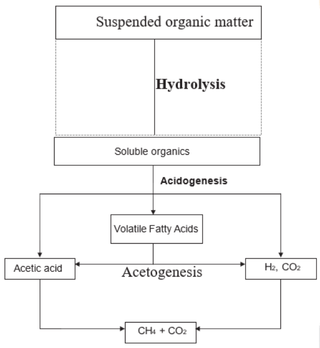

Fig.1.1. Subsequent steps in the anaerobic digestion process

3.2.1. Acidogenesis and hydrolysis

The first stage of anaerobic digestion involves hydrolyzing complex particulate material (polymers) into simpler dissolved materials (smaller molecules), which can pass through the cell membranes of the fermentative bacteria. This is necessary because microorganisms cannot assimilate particulate organic matter. The enzymes secreted by the hydrolytic fermentative bacteria operate to dissolve particulate materials into dissolved materials. In anaerobic environments, polymer hydrolysis typically proceeds slowly, and a number of variables may influence the extent and rate of substrate hydrolysis. (Lettinga et al., 1996)

- operational temperature of the reactor
- residence time of the substrate in the reactor
- substrate composition (e.g., lignin, carbohydrate, protein and fat contents)
- size of particles
- pH of the medium
- concentration of products from hydrolysis (e.g., volatile fatty acids)

The fermentative bacteria's cells break down the soluble products from the hydrolysis phase into a number of simpler chemicals, which are then expelled by the cells. Volatile fatty acids, alcohols, lactic acid, carbon dioxide, hydrogen, ammonia, and hydrogen sulphide are among the substances created, along with new bacterial cells.

A vast and varied range of fermentative bacteria perform acidogenesis. The typical species are members of the families Bacteroidaceaea, which are typically found in digestive tracts and are involved in the breakdown of amino acids and sugars, and the Clostridia group, which includes anaerobic species that produce spores and can survive in extremely harsh settings.

3.2.2. Acetogenesis

The products produced during the acidogenic phase are converted into a substrate suitable for methanogenic microorganisms by acetogenic bacteria. Acetogenic bacteria are thus components of a metabolic intermediate that generates a substrate for methanogenic microorganisms. Acetogenic bacteria produce acetic acid, hydrogen, and carbon dioxide as their byproducts.

A significant amount of hydrogen is created during the synthesis of acetic and propionic acids, which lowers the pH of the aqueous medium. However, hydrogen is utilised in the medium in one of two ways:

I.by microorganisms known as methanogens, which combine hydrogen and carbon dioxide to create methane; and

II.by the synthesis of organic acids like propionic and butyric acids, which are created when acetic acid, hydrogen, and carbon dioxide react. Only hydrogen and acetate can be utilised directly by methanogenic microorganisms out of all the compounds that acidogenic bacteria metabolize. However, at least 50% of the biodegradable COD is transformed into propionic and butyric acids, which are then broken down by acetogenic bacteria into acetic acid and hydrogen.

3.2.3. Methanogenesis

The methanogenic archaea carry out the last stage of the total anaerobic breakdown of organic molecules into methane and carbon dioxide. Acetic acid, hydrogen or carbon dioxide, formic acid, methanol, methylamines, and carbon monoxide are just a few of the substrates they utilise. Methanogenic microorganisms are split into two major types based on their affinity for substrate and level of methane production, one of which makes methane from acetic acid or methanol and the other from hydrogen and carbon dioxide, as follows:

(i)acetolactic methanogens, which use acetate, and

(ii) hydrogenotrophic methanogens, which use hydrogen.

3.3. Factors Affecting Anaerobic Digestion of Medical Waste

Within the anaerobic environment, various important parameters affect the rates of the different steps of the digestion process-

3.3.1. Temperature regime

Due to its quicker reaction times and greater load carrying capacity, thermophilic AD (55–70 °C) has a rate advantage over mesophilic digestion (37 °C) and, as a result, is more productive. However, during thermophilic AD, acidification may take place, preventing the formation of biogas. Other drawbacks have been observed, including diminished stability, poor methanogenic performance, low-quality effluent, greater toxicity and vulnerability to environmental conditions, higher investments, and higher net energy input. Furthermore, compared to the mesophilic process, this mechanism is more susceptible to environmental changes. Mesophilic systems have increased bacterial richness and better process stability, but they also produce less methane and have problems with biodegradability and nutrient imbalance. Therefore, thermophilic hydrolysis/acidogenesis and mesophilic methanogenesis, which are compatible with a two-phase anaerobic digestion process, would be the ideal conditions for AD. Organic waste has also been treated using AD at ambient/seasonal temperatures. Despite not requiring an additional heat source, this process produces less methane and is less stable than the mesophilic process as a result of environmental temperature variations. When treating co-substrates with high protein, lipid, and inert solid content concentrations, hyperthermophilic AD shows increased resilience. (Lee et al. 2009)

However, AD microorganisms are very sensitive to temperature changes which affect hydrogen and methane production, and the decomposition of organic materials. Decreases in temperature result in decreases in the VFA production rate, the ammonia concentration, the substrate utilization rate (E. J. Bowen et al.2014) and the metabolic rate of the microorganisms and increased ‘start-up’ times, thus decreasing yields. Increased pH, hydrolysis of organic particulates and methane potential have been obtained by increasing digester temperatures. Furthermore, linear correlations between TAN and temperature (20–60 1C) and biogas production between temperatures of 10 1C and 20 1C (D.T. Hill et al., 2001) have been observed.

3.3.2. pH

The products and processes of digestion are directly impacted by the operational pH. According to reports, the optimal pH range for AD is 6.8 to 7.4. Changes in pH have a big impact on how quickly bacteria grow. From 6 at pH 4.0 to 14 at pH 7.0, the relative abundance of microbial species has been seen to rise. When anaerobic acidogenesis is taking place in a chemostat culture, Clostridium butyricum appears to be the dominant bacterial species at pH 6.0, and Propionibacterium species appear to be dominant at pH 8. Controlling the pH level to achieve optimal microorganism development represents one potential technique to minimise ammonia toxicity caused by an elevated concentration of free ammonia (FA). A significant positive correlation has also been observed between hydrolysis and pH (Zhang et al.,2009). Therefore, the hydrolysis rate constant is considered to be pH dependent. It should be emphasized that both methanogenic and acidogenic microorganisms have optimal pH levels. Methanogenesis is most efficient at pH 6.5–8.2, and the optimal pH is 7.0 (Lee et al., 2009). At pH values below 6.6, methanogens grow much more slowly, and at pH values higher or lower than 6.6, methanogenic bacteria are less active. A two-stage AD process that separates the hydrolysis/acidification and acetogenesis/methanogenesis processes is the preferred mode of operation because the pH range for acidogenesis was between 5.5 and 6.5.

3.3.3. Solid to water content

To create a slurry with the proper consistency, water and raw ingredients should be combined. If the slurry is either too thin or too thick, the creation of biogas is ineffective. Depending on the type of raw material utilised, the ideal solid concentration can range from 7 to 25% (sewage waste has a very low solid content; the ideal amount can be reached by adding solid materials such as crop leftovers, weed plants, etc.).

3.3.4. Retention period:

The retention period is the length of time that the organic material stays in the digester for the purpose of producing biogas. Depending on the kind of feedstock and the temperature being used, the retention period will change. The two important retention times in the anaerobic digestion process are the solids retention time (SRT) and the hydraulic retention time (HRT). The SRT stands for the amount of time that bacteria and sediments stay inside the digester. Substrate retention time (HRT) is a term that is frequently used. It is the amount of time the input slurry spends inside the digester between the time of entry and exit.

3.3.5. Organic loading rate:

The production of biogas during anaerobic digestion is greatly influenced by the organic loading rate (OLR), especially when the digestion is conducted in continuous flow mode. OLR is a metric for the anaerobic digestion system's capability for biological conversion The quantity of raw materials (kg of volatile solids) delivered to the digester per unit volume per day can be used to express it. Acid buildup brought on by overloading easily impacts the digestive tract. Depending on the kind of raw material, retention period, and process temperature, the ideal loading rate is between 0.5 kg and 2 kg of total volatile solids per unit volume of the digester each day.

3.3.6.C/N ratio:

The relationship between the amount of carbon and nitrogen present in the raw materials is represented by the C/N ratio. The carbon-to-nitrogen (C/N) ratio is one of the important factors in the production of biogas. The elements carbon (in the carbohydrates) and nitrogen (in the form of proteins and ammonia nitrates) are the major food sources for anaerobic bacteria. The consumption of carbon by bacteria is 30 times faster than the consumption of nitrogen. Therefore, for optimum rate, the availability of carbon in the substrate should be 20–30 times higher than nitrogen (i.e., a C/N ratio between 20 and 30). (K. Fricke et al., 2005). Low levels of biogas production occur when methanogens quickly consume nitrogen when the C/N ratio is high. A lower C/N ratio causes ammonia to build up at pH levels that are hazardous to methogens (over 8.5). Co-digesting substrates with substrates with a lower C/N ratio will help keep the digester's C/N ratio at its ideal level. The influence of different feeds' C/N ratios on the generation of biogas revealed that a C/N ratio of 26:1 produces the most biogas compared to other ratios.

4. Biogas Composition and Energy Potential

4.1. Composition of Biogas Produced from Medical Waste

The chemical makeup of biogas produced from medical waste might vary depending on the waste type, the anaerobic digestion process used, and the operational conditions. But in biogas produced from medical waste, methane (CH_4), carbon dioxide (CO_2), and traces of other gases are frequently found.

4.1.1. Methane (CH_4):

Methane is the primary component of biogas and is the desired energy-rich gas. The methane content in biogas from medical waste can vary but is typically in the range of 50% to 70%. Higher methane content is generally desirable for the efficient utilization of biogas as a fuel.

4.1.2. Carbon Dioxide (CO_2):

Carbon dioxide is a byproduct of anaerobic digestion and is commonly found in biogas. Its content in biogas from medical waste can range from 30% to 45%. The presence of carbon dioxide affects the calorific value of biogas and reduces its energy content.

4.1.3. Traces of Other Gases:

Biogas may contain small amounts of other gases such as nitrogen (N_2), hydrogen sulfide (H_2S), water vapor ($H2_O$), and traces of volatile organic compounds (VOCs). The concentrations of these gases are typically low but can vary depending on the specific waste composition and process conditions.

4.1.4. Calculating the Energy Potential of Biogas

4.1.4.1. Total Solids (TS %): It is the amount of solid present in the sample after the water present in it is vaporized.
The sample, approximately 10 gm is taken and poured in foil plate and dried to a constant weight at about 105 ^{0}C in the furnace.

TS % = (Final weight/Initial weight) * 100

4.1.4.2. Volatile Solids (VS %): Dried residue from Total Solid analysis weighed and heated in crucible for 2hrs at 500 ℃ in furnace. After cooling crucible residue weighed.

VS % = [100-(V3-V1/V2-V1)] * 100

V1= Weight of crucible.
V2= Weight of dry residue & crucible.
V3= Weight of ash & crucible (after cooling)

4.1.4.3. Volatile Fatty Acid (VFA): Volatile fatty acids (VFA's) are fatty acids with carbon chain of six carbons or fewer. They can be created through fermentation in the intestine. Examples include acetate, propionate, butyrate. There are many titrations method for VFA measurement. I used two methods for VFA measurement.

Method 1

1. Take 100 ml sample in beaker
2. Filter the sample.
3. Check pH of the filtrate.
4. Take 20 ml of filtrate and add 0.1M HCl until pH reaches 4
5. Heat in the hot plate for 3 mins
6. After cooling titrate with 0.01M NaOH to take pH from 4 to 7.
7. Amount of HCl & NaOH recorded

Total VFA content in mg/l acetic acid = (Volume of NaOH titrated) * 87.5

Method 2:

- Titration procedure for measurements of VFA and alkalinity according to Kapp: Before analysis, the sample needs to be filtered through a 0.45µm membrane filter.
- Filtered sample (20-50ml) is put into a titration vessel, the size of which is determined by the basic requirement to guarantee that the tip of the pH electrode is always below the liquid surface.
- Initial pH is recorded
- The sample is titrated slowly with 0.1N sulphuric acid until pH 5.0 is reached. The added volume A1 [ml] of the titrant is recorded.
- More acid is slowly added until pH 4.3 is reached. The volume A2 [ml] of the added titrant is again recorded.
- The latter step is repeated until pH 4. 0 is reached, and the volume A3 [ml] of added titrant recorded once more.
- A constant mixing of sample and added titrant is required right from the start to minimize exchange with the atmosphere during titration.

Calculation scheme according to Kapp:

$$Alk = A * N * 1000 / SV$$

Alk = Alkalinity [mmol/l], also referred to as TIC (Total Inorganic Carbon).
A = Consumption of Sulphuric acid (H_2SO_4, 0.1N) to titrate from initial pH to pH 4.3 [ml]. A= A1 + A2 [ml].
N = Normality [mmol/l].
SV = Initial sample volume [ml].

$$VFA = (131340 * N * B / 20) - (3.08 * Alk) – 10.9$$

VFA = Volatile fatty acids [mg/l acetic acid equivalents].
N = Normality [mmol/l]
B = Consumption of sulphuric acid (H_2SO_4, 0.1N) to titrate sample from pH 5.0 to pH 4.0 [ml], due to HCO_3/CO_2 buffer.
B = A2 + A3 [ml]
SV = Initial sample volume [ml] Alk = Alkalinity [mmol/l]

4.1.4.4. A/TIC-ratio

The A/TIC method was developed at the Federal Research Institute for Agriculture (FAL) in Braunschweig, Germany. Used as an indicator of the process stability inside the digester, it expresses the ratio between Volatile Fatty Acids and buffer capacity (alkalinity), or in other words the amount of Acids (A) compared to Total Inorganic Carbon (TIC).

$$\frac{A\,[mg/l] = VFA\,[mg/l]}{TIC\,[mg/l] = Alkalinity\,[mg/l]}$$

4.1.4.5. Organic content

Organic dry matter weighs the sample and weigh remaining ashes Organic content = {Mass of TS - Mass of ashes}/Mass of TS

5. Benefits and Challenges of Biogas Production from Medical Waste

5.1 Environmental Benefits

Biogas production from medical waste offers several environmental benefits. Here are some of the key benefits along with a reference for further reading:

5.1.1. Renewable Energy Generation: One green energy source is biogas, which is created from medical waste. It can be used to produce electricity or heat or to take the place of fossil fuels. In order to reduce their dependency on non-renewable energy sources and assist reduce greenhouse gas emissions, medical facilities may employ biogas.

5.1.2. Waste Reduction: Biogas is produced by the anaerobic digestion of organic components in medical waste. The quantity of waste that must be dumped in landfills is reduced by this process. By avoiding medical waste from being dumped in landfills, biogas generation reduces the environmental impact of trash accumulation and methane emissions.

5.1.3. Methane Emission Reduction: Methane is a substantial contributor to climate change. Anaerobic digestion uses methane produced during the breakdown of organic waste in medical waste to produce biogas. Biogas production aids in lowering methane emissions, which have a greater potential to cause global warming than carbon dioxide. Methane is captured and used as a fuel source.

5.1.4. Pathogen Destruction: Through a controlled anaerobic digestion process, pathogens found in medical waste may be effectively removed while biogas is being produced.Pathogens are either destroyed or rendered inactive during digestion, which reduces the risk of disease transmission and overall enhances public health and safety. During digestion, specific environments with high temperatures are formed.

However, there are several challenges involved in producing biogas from medical waste, such as operational concerns, efficient waste segregation, and regulatory compliance. It is essential to adhere to local regulations, implement effective waste management practises, and ensure the safe handling and processing of medical waste. (Prasad et al., 2019)

5.2 Economic Benefits

Biogas production from medical waste offers several economic benefits. Here are some of the key benefits along with a reference for further reading:

5.2.1. Cost Savings: By balancing energy costs, biogas production can result in cost savings. Hospitals and other healthcare institutions can use the biogas generated from medical waste as an alternative energy source to lessen their dependency on traditional energy sources and to cut their energy expenditures.

5.2.2. Revenue Generation: Biogas production can generate revenue through the sale of excess biogas or by-products such as digestate. The biogas can be used for electricity generation or as a renewable natural gas (RNG) fuel for vehicles. The sale of excess biogas or RNG can create additional income streams for medical facilities.

5.2.3. Waste Management Cost Reduction: Medical waste can be digested anaerobically to lower waste management expenses. The volume of trash is reduced during biogas production, possibly lowering disposal and transportation costs related to the management of medical waste.

5.2.3. Carbon Credits and Incentives: Medical waste biogas generation is eligible for carbon credits and incentives. For initiatives involving renewable energy, such as the generation of biogas, governments and regulatory agencies may provide financial incentives, tax breaks, or subsidies. These incentives can help medical institutions, increasing the economic sustainability of biogas generation.

However, there are issues with the financial elements of producing biogas from medical waste as well. The initial investment costs, ongoing expenditures, costs associated with regulatory compliance, and market variables like shifting energy prices and the availability of financial support are a few examples of these difficulties. (Zhang et al.,2018)

5.3 Challenges of Biogas Production from Medical Waste

5.3.1Technological Challenges

Biogas production from medical waste offers several benefits, but there are also technological challenges that need to be addressed for successful implementation. Here are some key technological challenges along with a reference for further reading:

5.3.1.1. Feedstock Composition and Variability: The content of medical waste might fluctuate, which makes it difficult to optimise the biogas generation process. The effectiveness of anaerobic digestion can be impacted by the varied organic content, moisture content, and presence of medications or chemicals in medical waste. For sustained biogas generation, a uniform and consistent feedstock composition is essential.

5.3.1.2. Inhibitory Substances: The anaerobic digestion process may be hampered by the presence of inhibitory materials in medical waste, such as disinfectants, antibiotics, and heavy metals. The bacteria responsible for producing biogas may be toxicly affected by these compounds, which might result in unstable processes or lower gas outputs. Medical waste biogas generation has a technological hurdle in the form of measures to lessen the inhibitory effects of these compounds.

5.3.1.3. Process Monitoring and Control: For effective biogas generation, ideal process conditions must be kept. It can be technically difficult to monitor and regulate variables like temperature, pH, and organic loading rates in large-scale biogas facilities. To maintain steady operation and maximize gas output, it is vital to develop reliable process monitoring and control systems.

5.3.1.4. Pathogen Inactivation: It may be necessary to properly inactivate infectious microorganisms in medical waste throughout the biogas generation process. Conditions for digestion must be carefully planned and managed to ensure optimal pathogen eradication. A major technological issue in the generation of medical waste biogas is the development and application of trustworthy methods for pathogen inactivation.

The continuous study, development, and innovation in the field of medical waste biogas generation are necessary to meet these technological obstacles. To overcome these obstacles and improve the procedure for effective and secure biogas generation, cooperation between waste management specialists, engineers, and researchers is crucial. (Liu et al.,2020)

5.3.2. Regulatory and Safety Challenges

Biogas production from medical waste offers various benefits, but there are also regulatory and safety challenges associated with its implementation. Here are some key challenges related to regulations and safety along with a reference for further reading:

5.3.2.1. Regulatory Compliance: Regulations and permissions relating to waste management, environmental protection, and public health and safety apply to the production of biogas from medical waste. To guarantee proper management, treatment, and disposal of medical waste, compliance with these standards, which might differ among areas and jurisdictions, is crucial. Regarding paperwork, reporting, and adherence to strict standards, meeting regulatory obligations can be difficult.

5.3.2.2. Safety Precautions: Medical waste may contain hazardous items such pathogenic bacteria, drugs, and chemicals. The safety of people who handle medical waste during collection, transport, and processing is crucial. The right safety procedures, personal protective equipment (PPE), and training programmes must be put in place in order to reduce exposure to potentially harmful substances and preserve the welfare of employees.

5.3.2.3. Odor and Air Emissions Control: Volatile organic compounds (VOCs) and hydrogen sulphide (H_2S) are two air emissions and odorous substances that can be produced during the biogas generation process from medical waste. These emissions can be bothersome and raise questions about human health and the environment. It can be technically and legally challenging to implement efficient odour control methods and gas treatment systems to minimise emissions and meet air quality regulations.

5.3.2.4. Public Perception and Acceptance: Due to perceived hazards connected with waste management and possible emissions, biogas generating facilities, particularly those processing medical waste, may encounter public concerns and opposition. Gaining approval and backing from regional stakeholders requires cultivating public confidence, resolving community issues, and increasing transparency regarding safety precautions and legal compliance.

The waste management industry, environmental agencies, health departments, and industry stakeholders must work closely together to address these regulatory and safety issues. The generation of biogas from medical waste can pose certain risks, but these can be reduced by regular monitoring, risk assessments, and periodic safety audits. (Zhang et al.,2018)

7. Future Prospects and Potential Applications

7.1. Integration with healthcare facilities

Due to the possible environmental and health dangers associated with medical waste, its sustainable handling has become a critical problem. A viable option that not only tackles waste management issues but also offers a sustainable energy source is the generation of biogas from medical waste. This essay examines the prospects for the future and potential uses of biogas made from medical waste. It analyses the situation of current medical waste management practices while underlining the drawbacks and difficulties of using traditional disposal techniques. It also looks at various technology and feedstock sources for the biogas generation process. The article also covers the environmental and financial advantages of producing biogas from medical waste, highlighting its part in reducing greenhouse gas emissions and boosting the creation of sustainable energy.

7.1.1. Initialization

Medical waste creation has significantly increased as a result of the expanding healthcare sector, demanding efficient waste management techniques. Traditional ways of disposing of medical waste, such as landfilling and burning, present serious environmental and health risks. A viable approach that not only tackles waste management issues but also produces sustainable energy is the creation of biogas from medical waste.

7.1.2. Current Medical Waste Management Situation

This section gives a general summary of the ways that medical waste is currently managed, highlighting the difficulties and restrictions that come with using traditional disposal techniques. It emphasizes the requirement for ecologically responsible and sustainable waste management techniques. 3. Producing Biogas from Medical Waste

7.1.3. Process of Producing Biogas

This section examines the various methods used for the digestion of medical waste as well as the biogas generation process. Co-digestion, anaerobic digestion, and other pertinent processes are covered.

7.1.4. Options for Feedstock

The many feedstock choices for producing biogas from medical waste are presented in this part. It encompasses a variety of medical waste, such as pathological waste, blood products, surgical waste, and expired medications.

7.1.5. Economic and Environmental Benefits

The advantages of producing biogas from medical waste for the environment and the economy are covered in this section. It examines how biogas might help cut greenhouse gas emissions as well as the possible business prospects connected to environmentally friendly energy production and waste management.

7.1.6. Possibly Useful Applications

This section focuses on the possible uses for biogas produced from medical waste. It covers the production of heat, power, and the use of biogas as a fuel source in the industrial and transportation sectors.

7.1.7. Finalisation

The future possibilities and potential uses of biogas produced from medical waste are summarised in the paper's conclusion. It underscores the significance of implementing ethical waste management procedures and the value of using biogas as a green energy source.

7.2. Options for Utilizing Biogas

A potential method for managing trash and generating renewable energy is the creation of biogas from medical waste. Biogas, a combination predominantly made up of methane (CH4) and carbon dioxide (CO2), may be used in a variety of ways and is a flexible energy source. This section examines the possibilities for biogas' use in the future while underlining its substantial benefits for environmental sustainability, energy security, and waste management.

7.2.1. Power Production:

Internal combustion engines (ICE), gas turbines, and fuel cells are just a few of the ways that biogas may be used to produce power. Reciprocating engines and microturbines, which are ICE-based power production technologies, have great electrical efficiencies and may be incorporated into current power networks. Large-scale power plants frequently employ gas turbines because they have bigger capacity and can run on a wider variety of gas compositions. Additionally, fuel cells provide power with efficiency and little emissions, making them appropriate for decentralized applications.

7.2.2. Heat Generation:

Using biogas to generate heat is a useful use as well. In order to generate heat for commercial or industrial activities, space heating, or water heating, biogas can be burned directly in boilers or furnaces. Methane's high calorific value means that heat is generated efficiently and consistently, making biogas an appealing replacement for fossil fuels in a variety of industries, including agriculture, healthcare, and residential settings.

7.2.3. Combined Heat and Power (CHP):

CHP systems, commonly referred to as cogeneration, employ biogas to produce both electricity and usable heat simultaneously. CHP systems achieve high levels of total energy efficiency by using the waste heat generated during the production of electricity. They have uses in hospitals, wastewater treatment facilities, district heating systems, and other places where a constant supply of heat and power is needed.

7.2.4. Biomethane Injection and System Integration:

Upgraded biogas, also known as biomethane, can be utilized as car fuel or pumped into the natural gas system. In order to produce biomethane, impurities like CO2 and other pollutants must be removed, leaving behind a composition of gas that is comparable to that of natural gas. The current natural gas network may be made more renewable and decarbonized by adding biomethane to it. Additionally, it makes it possible to use biomethane as a sustainable fuel for transportation, which lowers greenhouse gas emissions in the industry.

7.2.5. Biochemical Conversion:

Using biochemical conversion techniques like anaerobic digestion and fermentation, biogas may be transformed into useful chemicals and biofuels. These procedures can produce bio-based goods such as organic acids, platform chemicals, bioethanol, and biodiesel. The notion of a biorefinery may be realized by combining these conversion routes with the generation of biogas from medical waste, maximizing resource efficiency and fostering a circular economy.

Biogas made from medical waste has a lot of potential for a sustainable future. The value of biogas may be maximized by implementing a variety of utilization alternatives, including power and heat generation, CHP systems, biomethane injection, and biochemical conversion. These programs aid in the management of waste, the security of the energy supply, and the reduction of greenhouse gas emissions. Accepting these potential outcomes will speed up the shift to a more sustainable and circular economy. (He et al., 2020, Ong et al.,2018)

7.3. Opportunities for Research and Development

Due to its hazardous nature and possible environmental effects, the efficient management and disposal of medical waste present considerable issues. By generating useful renewable energy from the organic portion of trash, biogas generation from medical waste presents a possible option. The research and development potential in the area of producing biogas from medical waste are examined in this article, with an emphasis on significant developments, ground-breaking technology, and promising future directions. Sustainable waste management, lower greenhouse gas emissions, and the production of renewable energy for varied uses are some of the possible advantages. This study offers perceptions on the state of the art at the moment, identifies research gaps, and suggests relevant directions for more investigation.

7.3.1. Initialization

The relevance of medical waste management and the environmental difficulties posed by conventional disposal techniques are briefly discussed in the introductory section. The production of biogas is highlighted as a potential option and the necessity for sustainable alternatives is emphasised.

7.3.2. Technology for Producing Biogas

The several processes used to produce biogas from medical waste are covered in this section, including anaerobic digestion, co-digestion, and thermal gasification. It provides a thorough grasp of the many strategies accessible by examining their operating principles, benefits, and drawbacks.

7.3.3. Classification and Pre-treatment of Medical Waste

The description of medical waste is covered in this article, along with its composition, variability, and consequences for the production of biogas. In order to increase the effectiveness of the biogas generation process, the significance of pre-treatment techniques such sterilisation, shredding, and maceration is emphasised.

7.3.4. Process Control and Optimisation

The process optimisation and control techniques for producing biogas from medical waste are the main topics of this section. It analyses methods including co-digestion with different waste streams, supplementing with co-substrates, and microbial modification and covers crucial variables like temperature, pH, substrate-to-inoculum ratio, and hydraulic retention period.

7.3.5. Utilisation and Applications of Biogas

This section discusses the use and applications of biogas produced from medical waste. It investigates its potential as a fuel for vehicles as well as a source of heat and energy. It is also investigated how biogas producing systems may be integrated with current infrastructure.

7.3.6. Economic and Environmental Analysis

This section assesses the economic and environmental effects of producing biogas from medical waste. It talks about lowering greenhouse gas emissions, reusing garbage, and the possibility of economic savings via energy recovery. Methodologies for cost-benefit analysis and life cycle analysis are taken into account.

7.3.7. Difficulties and Prospects for the Future

This section discusses the difficulties and obstacles preventing the widespread use of biogas produced from medical waste. It also points out areas for further research and suggests strategies for addressing these difficulties, such as better waste segregation, technology development, and regulatory support.

7.3.8. Finalization

The paper's main findings are summed up in the conclusion, which highlights the possibility of producing biogas from medical waste as a sustainable waste management and energy-generating alternative. It emphasizes the significance of ongoing research and development initiatives to maximize the advantages and get beyond current constraints. (Bajaj et al.,2021, Zhang et al.,2014)

8. Conclusion

The production of biogas from medical waste has become a potential method for managing trash sustainably and producing renewable energy. The thorough assessment of the literature exposes the potential and difficulties involved in this approach. Medical waste presents technological difficulties for effective biogas generation due to its varied composition and the presence of harmful compounds. However, improvements in operational variables, such as temperature control and substrate pre-treatment, as well as knowledge of the dynamics of microbial communities, can optimize the procedure and boost biogas output. In addition to providing a sustainable energy source, the conversion of medical waste into biogas tackles environmental issues with waste disposal by lowering greenhouse gas emissions and reducing reliance on fossil fuels. Anaerobic digestion of medical waste has the potential to be used instead, which would have the twin benefits of waste management and energy recovery. To guarantee secure and appropriate waste disposal procedures, compliance with regulatory frameworks, such as those established by the World Health Organisation and Environmental Protection Agency, is essential. In order to maximize the generation of biogas from medical waste, the study emphasizes the need for more study and technology developments, while also investigating novel strategies and system arrangements. Utilizing the potential of biogas production from medical waste will allow us to develop a waste management plan that is both more effective and sustainable while also assisting the worldwide transition to a low-carbon future.

I. ACKNOWLEDGMENT

I would like to thank my colleague Mr. Kamthong for his continuous help and support, as well as Dr. Rajesh Jesudasan for his supervision.

REFERENCES

[1] Angelidaki I, Ellegaard L, Ahring BK. Applications of the Anaerobic Digestion Process. Appl Microbiol Biotechnol. 2009;81(4): 657-662.
[2] Appels L, Baeyens J, Degreve J, Dewil R. Principles and potential of the anaerobic digestion of waste-activated sludge. J Environ Manage. 2011;92(8): 2354-2370.
[3] Bowen EJ, Dolfing J, Davenport RJ, Read FL, Curtis TP. Low-temperature limitation of bioreactor sludge in anaerobic treatment of domestic wastewater. Appl Environ Microbiol. 2009;75(21): 7014-7016.
[4] Behera S. Medical waste management and biogas production: A review. J Clean Prod. 2020;250: 119516.
[5] Bajaj M, Summerbell R, Künzli N, et al. medical waste management in the context of COVID-19: A review of contemporary knowledge and practice. Sustainability. 2021;13(9): 4881. doi:10.3390/su13094881
[6] Chanakya HN, et al. Biogas from medical waste: A comprehensive review. Waste Manag. 2019;87: 692-706.
[7] Fang C. Biogas production from food-processing industrial wastes by anaerobic digestion. Water Sci Technol. 2011;63(2): 384-389.
[8] Gupta R, Kumar V, Sreekrishnan TR. Microbial community dynamics during anaerobic digestion of medical waste: Influence of operational parameters. J Environ Manage. 2020;261: 110251.
[9] He Y, Angelidaki I. Biogas and methane yield from medical waste: a critical review. Waste Manag. 2020;102: 375-387.
[10] Ismail S, et al. Environmental impact of healthcare waste management: A review. Environ Technol Innov. 2021;22: 10135.
[11] Johnson C, Miller T, Brown K. Biogas production from medical waste: A pilot study on the potential of diverting medical waste to anaerobic digestion. Waste Manag. 2021;121: 94-102. doi: 10.1016/j.wasman.2020.12.028
[12] Liu Y, Zhang Y, Li Q, Yang G, Wang X. Biogas production from medical waste: Challenges and opportunities. Waste Manag. 2020;102: 289-298. doi: 10.1016/j.wasman.2019.11.022
[13] Lee M, Hidaka T, Hagiwara W, Tsuno H. Comparative performance and microbial diversity of hyperthermophilic and thermophilic co-digestion of kitchen garbage and excess sludge. Bioresour Technol. 2018;250: 775-781.
[14] Lee DH, Behera SK, Kim JW, Park H-S. Methane production potential of leachate generated from Korean food waste recycling facilities: A lab-scale study. Waste Manag. 2013;33(5): 1103-1108.
[15] Ong SA, Toh PS, Ng HK. A review of anaerobic digestion systems for biodegradable waste: Configurations, operating parameters, and current status. Waste Biomass Valoriz. 2018;9(2): 145-175.
[16] Panda AK, et al. Biogas production from medical waste. In: Biogas: A Renewable Energy Source. Springer; 2018. p. 275-289.
[17] Prasad G, Siva Ilango M. Biogas production from medical waste: A review. Renew Sustain Energy Rev. 2019;109: 406-416. doi: 10.1016/j.rser.2019.04.037
[18] Smith A, Johnson J, Davis J. Anaerobic digestion of medical waste: A sustainable solution for renewable energy production. Waste Manag Res. 2018;36(5): 437-445.
[19] Smith JA, Francis D, Sue R. Environmental impacts of medical waste management. J Environ Health Res. 2020;26(3): 123-138.
[20] Smith A, Johnson B, Thompson D. Anaerobic co-digestion of healthcare waste with municipal wastewater sludge: An energy and emission assessment. Waste Manag. 2018; 75:1-10. doi: 10.1016/j.wasman.2018.02.017
[21] Soubes M, Muxf L, Fernandez A, Tarlera S, Queirolo M. Inhibition of methanogenesis from acetate by Cr +3 and ammonia. J Environ Health Res. 2021;26(3): 123-138.
[22] U.S. Environmental Protection Agency. Medical waste management regulations. Environmental Protection Agency; 2021.
[23] World Health Organization. Safe management of wastes from healthcare activities. World Health Organization; 2019.
[24] World Health Organization (WHO). Safe management of wastes from health-care activities. 3rd ed. Geneva: World Health Organization; 2014. Available from: https://www.who.int/publications/i/item/9789241548564
[25] World Health Organization. Safe management of waste from health-care activities. Geneva: World Health Organization; 2021.
[26] Zhang Y, Su D, Wang X, Dong R, Li Y, Li Y, Wang X. Biogas production from medical waste: A review on recent developments and future prospects. Waste Manag. 2018; 79:311-323. doi: 10.1016/j.wasman.2018.08.041
[27] Zhang C, Su H, Baeyens J, et al. Reviewing the anaerobic digestion of food waste for biogas production. Renew Sustain Energy Rev. 2014; 38:383-392. doi: 10.1016/j.rser.2014.05.038
[28] Zhang Y, Li Q, Yang G, Wang X. Biogas production from medical waste: Challenges and opportunities. Waste Manag. 2020; 102:289-298. doi: 10.1016/j.wasman.2019.11.022