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Review article

Repurposing food waste for renewable energy: Insights and challenges in biogas production

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ABSTRACT

Biogas production through the anaerobic digestion of food waste (FW) presents a sustainable and eco-friendly alternative to traditional fossil fuels. This review explores how different types of food waste can serve as adequate feed stock for biogas generation, highlighting the influence of environmental conditions and microbial activity on optimizing methane yields. The process follows two primary biological stages: the breakdown of complex organic materials into simpler compounds and their conversion into methane. At present, the urgent need to address greenhouse gas emissions and manage waste more effectively, biogas production from FW offers a valuable opportunity to produce renewable energy while reducing carbon footprints. This review is focusing on the biogas production rate under varying substrate ratios and operational conditions, using a specially designed aluminum-based digester to boost internal temperatures and improve efficiency. As per the literature study, aluminum digesters—especially those coated with black paint—significantly enhanced methane production compared to conventional plastic digesters. Furthermore, kitchen waste, rich in organic content and readily available, proved to be an excellent raw material for anaerobic digestion (AD) . Careful control of key factors such as pH, temperature, and retention time are found to be essential for maximizing biogas yields during food waste digestion. Overall, this work emphasizes the dual advantages of converting food waste into energy and promoting sustainable waste management, positioning biogas as a vital contributor to a greener and circular economy.

1. Introduction

Biogas may be generated from food waste or any type of food waste through anaerobic digestion using different kinds of anaerobic bacteria (Chew et al., 2021). Anaerobic corrosion is a two-phase process where specific bacteria degrade or utilize a definite substrate. Acidic bacteria decompose complex organic matter into simpler sugars, glycerol, peptides, and alcohol in the first process. Another type of bacteria starts to transform these basic combinations into methane, once these compounds have been produced in sufficient quantities. Many of these methane-producing microorganisms are sensitive to their environment, and this can either inhibit or halt the production of methane completely (Cremonez et al., 2021). Cutting emissions of greenhouse gases, especially CO_2, has become even more critical, as encyclopedias suggest. Contributory influence by anthropogenic exertion in the energy and transportation sub-sectors is presently the driving force for carbon dioxide emissions from the application of highly conservative energy. Collectively, these papers indicate that

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through optimizing efficacy via engagement of necessary powers, the energy industry may be able to herald worthwhile improvements on emigration. It remains our option to avoid CO_2 from being emitted into the atmosphere through the use of biogas plants (Lamb et al., 2021).

This work illustrates a bio energy product of biogas, which aims and prospects for advertising from residual aggro-food bio-masses. It also describes debates on the strengths and weaknesses of several substrate kinds and plant technologies, as well as which instruments to identify the best approaches to improve the efficiency of advertisements are the most auspicious. Last of all, it defines the best process conditions (De Carvalho et al., 2022). Biogas can be generated from virtually all types of natural feed stock, comprising waste flows and prominent segments of the agricultural industry. On average, millions of tons of animal waste are produced in India every year. Animal feces, when collected from animals that have been exposed or cleaned inadequately, are known to cause significant pollution within the atmosphere and water sources (Atelge et al., 2020).

This review focuses on the rate of biogas production in a biogas plant that manufactures aluminum. Further, experiment with the different rates of kitchen waste to biogas products and their concatenation for the particularity of the retention time at varying temperatures. To date, the literature is rich in knowledge regarding the make-up of biogas products (CH_4 bits) and the temperature of the slurry's operation. In a way, to evaluate the maximal rate of the product biogas throughout this article. Moreover, comparing the rate at which they produce biogas out of kitchen trash and other sources of energy, such as coal, kerosene, and **liquefied petroleum gas** (LPG) that are used in cooking as per shown in Table 1 (Nsair et al., 2020).

Table 1: **Contrasting the different proportions of kitchen trash produced using biogas**

Character	Case - A6 kg (1:3)	Case - B8 kg (1:2)	Case - C10 kg (1:1.4)	Case - D12 kg (1:1)
Quantity of kitchen waste	6kg	8kg	10kg	12kg
Water	18 lt	16It	14It	12It
pH	7.3	7.4	7.7	7.9
Proportion of food waste to water	1:3	1:2	1:1.4	1:1
Inoculum	6It	6It	6It	6It
Overall biogas production (m^3)	0.21846	0.258157	0.12785	0.12168
Maximum methane fraction	42%	48%	44%	No
Duration of methane fraction production in days	3-11	3-15	18-22	No
Number of days methane fraction present	10	15	5	No

2. Sources of food waste

FW happens at every step of the food journey, from farms and factories to grocery stores and our own kitchens at home. Such places are in the canteen of colleges and schools, fruit peels, kitchen waste, etc., which create problems for others and cause harmful diseases. In my report, there is a modern solution to convert food waste into energy (Mashfy et al., 2022).

3. Food waste (FW): A valuable raw resource

The leading cause of large amounts of food or kitchen waste produced is population growth, (Fig. 1) together with economic development. In densely populated nations like India, FW is one of the most readily available feed stocks, contributing 30 to 50% of the overall amount of (MSW) municipal solid waste produced. Food waste is created in the form of cooked or raw food (waste grains, vegetables, and fruits) and amounts to 400 billion rupees (INR) annually. Because it is rich in organic matter and has a variety of nutritional sources, including proteins, lipids, and carbohydrates, FW can be an excellent source for the producing biogas (Kumar et al., 2023).

4. Experimental configuration and Equipment

To enable the digester (Fig. 2) and plate to intake the solar radiation directly, an aluminium biogas chamber with a slurry holding capacity of 30kg has been used in the outdoor simulation carried out above the ground (Fig. 2) Both digester height and perimeter have been estimated to be as follows: 0.38m height and 0.34m perimeter. Furthermore, both plates know their weight, depth, and perimeter were identified at 180 grams, 350 millimeters, and 300 millimeters, respectively (Khune et al., 2021). It is with this backdrop that aluminum essence can be used to raise the internal temperature of the digester, therefore moving the rate at which biogas production is higher. In the biogas factory was made up of aluminum, a calibrated thermocouple is used to measure the temperature of slurry using a digital temperature index with 0.1˚C accuracy (Manikandan et al., 2023).

5. Biogas production process

5.1 Preparing the feed stock

Organic waste products would include the collection of food remains, kitchen and farm garbage, and canteen wastes from schools and Universities. Pre-treatment: Collected waste sometimes pulverized or shredded to increase surface area, hence an increasing microbial activity. Other forms of pre-treatment include adjusting the moisture content to the optimum digestion levels (Meena et al., 2019).

Fig. 1. Images of food waste and kitchen waste

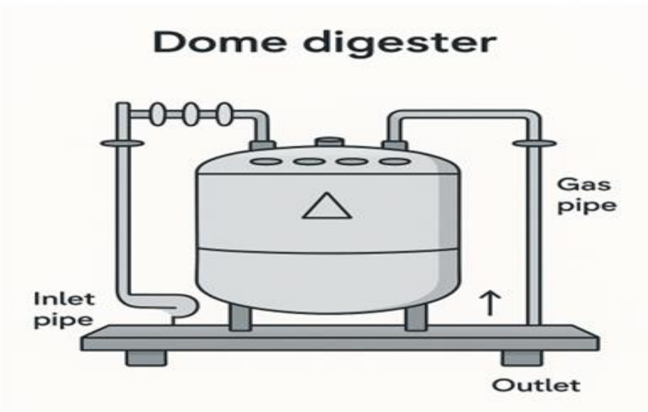

Fig. 2 An animated view of the dome digester

5.2 Filling of the biogas reservoir

Loading is a critical stage in anaerobic digestion, where treated organic feed stock, such as food waste and agricultural waste, is fed into the chamber. The feed stock requires proper pre-treatment in the form of grinding or shredding to maximize microbial activity and increase the surface area. With due caution, the treated feed stock is deposited into the air-proof chamber that is meant to keep the incomplete sentence (Smeets et al., 2010).

5.3 Anaerobic digestion

The entire process consists of four steps: hydrolysis, which involves the breakdown of large organic molecules into smaller ones; acidogenesis- whereby the small molecules are then converted to fatty acids and gases; acetogenesis-during which these acids are convert in to acetic acid, hydrogen and carbon dioxide; methanogenesis- at which stage these products are converted into carbon dioxide and methane by special bacteria to produce biogas. Biogas mainly consists of methane. It is a beneficial renewable source of energy for electricity, heating, or as fuel for vehicles. The remaining product is known as digestate. The digestate is rich in nutrients and may be used as fertilizers or for the amelioration of soil, contributing to sustainable farming (Sharma et al., 2023).

6. Steps involved in anaerobic digestion

6.1 Hydrolysis

Simpler compounds like sugars, amino acids, and fatty acids are individually broken down from larger and more complex chemical molecules like proteins, lipids, and carbs (Blair et al., 2021).

6.2 Enzymes

Specific enzymes produced by bacteria enable the breakdown (Blair et al. 2021). Importance: Hydrolysis is one of the crucial steps because it changes hard-to-dissolve organic material into substances that can dissolve. These substances can then be used by bacteria (Ranaei et al., 2020).

6.3 Acidogenesis

The soluble compounds created during hydrolysis are further broken down by the acid-loving bacteria. In this stage, ammonia, hydrogen, carbon dioxide, alcohols, and volatile fatty acids are produced (Ranaei et al., 2020). By-products such as Butyric acid, propionic acid, and acetic acid are also formed which are main product of this stage (Ranaei et al., 2020).

6.4 Acetogenesis:

Mechanism: Acetic acid is produced along with carbon dioxide and hydrogen by acetogenic bacteria from the volatile fatty acid (VFA) and the other end products of the acidogenesis (Karekar et al., 2022). Acetogenesis is important because methanogens, the bacteria will have responsibility of the next step, mainly use carbon dioxide, acetic acid and hydrogen (Karekar et al., 2022).

6.5 Methanogenesis

Methanogenic bacteria, which are strictly anaerobic bacteria, ferment acetic acid, hydrogen, and carbon dioxide to form methane gas, CH_4 and carbon dioxide, which together form biogas (Bharathiraja et al., 2018). The final product is biogas. Usually, this biogas contains about 50-70% methane. Methane is the fraction of biogas that makes it energetic (Haque et al., 2023).

7. Application of anaerobic digestion

Anaerobic digestion is currently one of the most popular modes of waste treatment andrenewable energy generation. Organic wastes enter in this process to produce food scraps, plant residues, and animal excreta through biogas and valuable digestate. In this process biogas is produced and it can be converted into electrical energy, heat, or biomethane formation, it is used as a clean and green fuel in transportation as an alternative to fossil fuels. At the same time, the digestate is a valuable fertilizer that improves soil health and cuts down the

The biological process that breaks down organic material without oxygen is called anaerobic digestion. This creates biogas and digestate, which help with waste management, decrease landfill use, and reduce greenhouse gas emissions. It also supports energy sustainability and recycling nutrients. This process is essential for a circular economy because it turns waste into valuable resources (Haque et al., 2023).

need for chemical fertilizers. This technology helps lower landfill waste and greenhouse gas emissions. It also promotes energy sustainability and nutrient recycling in farming (Ahmed et al., 2020).

8. Advantages of anaerobic digestion

Accordingly, anaerobic digestion is very beneficial method for the treatment of organic waste. It manages organic wastes effectively, minimizes landfill disposal, and cuts down the emission of greenhouse gases. It produces biogas, a form of renewable energy. In this respect, the biogas produced could be utilized for heating, electricity generation, or even as a fuel for vehicles, thereby reducing the consumption of fossil fuels as per shown in Table 2 Besides, the process produces digestate, a by-product rich in nutrients. Digestate can be used as a natural fertilizer to promote sustainable farming. Anaerobic digestion helps in creating valuable resources from the various waste materials. This supports a circular economy and helps the environment. It also contributes to energy independence (Saravanakumar et al., 2023).

9. Factors affecting biogas production and its economic benefits

Biogas production in AD is based on a number of key parameters, which are mainly include feedstock type and composition, temperature, pH value, retention time, and inhibitors. The characteristics and composition of the feedstock organic wastes and othera factors like its carbon-to-nitrogen ratio, determine the quality and the effectiveness of the biogas production are also important. Temperature is a very critical factor since mesophilic conditions around 35°C-40°C, and thermophilic conditions, around 50°C-60°C, remain quite optimal for microbial activity (Rabbani et al., 2023). A pH must be maintained in the range between 6.5 and 7.5 for the better growth and survival of methanogenic bacteria.The retention time period during which the feed stocks are kept inside the digester influences gas production; a more extended retention period allows for better digestion. In addition, substances such as ammonia, sulfides, or heavy metals are harmful to microbes when their concentrations are too high, which reduces biogas production. Managing these factors well is essential to getting the most biogas in anaerobic digestion processes (Rocha-Meneses et al., 2022).The production of biogas has considerable environmental and economic advantages. Environmentally, biogas production from the food waste decreases the amount of organic waste that goes to landfills, subsequently lowering methane emissions, which are a potent greenhouse gas. It also provides a renewable source of energy, reducing dependence on fossil fuels and lowering carbon emissions (Sánchez et al., 2023).

Table 2 Rate of biogas generated from kitchen trash compared to other energy sources such as coal, Kerosene, and LPG used for cooking (Sharma et al., 1999).

Criteria	Biogas (from Kitchen Waste)	LPG	Kerosene	Coal
Energy Content	20-25 MJ/m³	46 MJ/kg	43 MJ/kg	24 MJ/kg
Efficiency	55-65%	60-70%	50%	25-30%
Production Rate	0.4-0.6 m³ per kg of kitchen waste	Commercially produced and available	Commercially produced and available	Commercially produced and available
Environmental Impact	Low emissions, renewable, waste management	Lower emissions than coal and fossil fuels	Higher emissions than LPG, fossil fuel	Highest emissions, significant pollution
Cost	Low (after setup, fuel is free)	Variable, depends on market prices	Variable, depends on market prices	Variable, depends on market prices

This process converts the food waste into a nutrient-rich by-product that can replace chemical fertilizers, thus enabling the practice of sustainable agriculture and reducing soil and water pollution. Production of biogas helps farmers and businesses to be paid due to the usage of waste for energy production and proper fertilizers. It aids energy security by providing a substitute local, renewable source. Besides, there is a possibility of reducing waste management costs and enhancing rural development with the creation of new employment opportunities, which would advance sustainable development. Overall, it is essential in the transition to a more resource-efficient and circular economy (Manesh et al., 2020).

10. Biogas in India: Challenges, opportunities and emerging research

The biogas industry is confronted with a myriad of issues, such as high start-up costs, technical complications, and constant material supply (Mosavi et al., 2023). Construction and maintenance of biogas plants are extremely capital-intensive; this can be very cumbersome for small-scale practitioners. Technical challenges range from maintaining favorable conditions for AD to purifying the biogas and utilizing the resulting energy efficiently. Besides, the quality and quantity of organic substances are varying, which influences are the steadiness of biogas production (Uddin et al., 2023). Even with all these challenges, the future of biogas is bright due to enhanced technology, favorable governmental legislation, and increased awareness about the role of renewable energy sources. Novel concepts in the production of biogas, such as strengthening the digester design, efficient feedstock management, and biogas enhancement techniques, have made the process more viable and economical. As more people focus on sustainability and circular economy practices, biogas will probably be very important for cutting down waste, reducing greenhouse gas emissions, and offering a renewable source of energy in the future (Kucher et al., 2021). A biogas plant that gets bigger could make more biogas and help us use it in different ways. The best option for producing biogas and hydrogen/biohydrogen from FW, besides managing one of the most critical waste operation enterprises, is this. The generation of a biogas storehouse from FW is quite simple, using user-friendly technologies. Multiple operational advantages that green energy sources, such as biogas, provide, including a heat and power source. Based on this review, we found that the bioconversion of FW for hydrogen, ethanol, biodiesel, and methane is economically viable Sharma et al., 2024). (

11. Conclusion

Anaerobic digestion (AD) of food waste presents a sustainable and efficient method for managing organic waste while simultaneously producing renewable energy in the form of biogas. This biological process not only reduces the volume of food waste sent to landfills, thereby minimizing greenhouse gas emissions, but also generates nutrient-rich digestate that can be used as a biofertilizer. By converting organic waste into valuable resources, AD process supports circular economy principles, reduces environmental pollution, and contributes to energy security. As urban populations and food waste volumes grow, expanding the implementation of AD technology will be critical for achieving sustainable waste management and climate goals. By comparing various types of kitchen wastes in an aluminum biogas plant, it is observed that aluminum reactor is a better option for making biogas and also it is safe for the environment. Overall, observations indicated that metal absorbs more sunlight; this makes the inner temperature of the digester much warmer as compared to a plastic biogas plant. While, aluminum biogas plants are more expensive and have shorter life spans than those made of plastic, they produce more biogas and obtain more carbon credits. In tests, painting of the aluminum plant with black paint can increased biogas production and lengthened the life of the plant. As compared to the plastic anaerobic digestion reactor, a black-painted aluminum biogas plant may be ideal for producing biogas from food waste in the communities.

12. Future recommendations

12.1 Technology optimization and innovation

Future research should focus on enhancing the efficiency of AD systems through innovations such as two-stage digestion, thermophilic digestion, and advanced pre-treatment methods (e.g., hydrothermal, ultrasonic etc.). These improvements can increase biogas yield and reduce retention time.

12.2 Integration with circular economy models

AD should be integrated into broader circular economy strategies, including nutrient recovery (from digestate as biofertilizer), water reuse, and renewable energy generation. This creates closed-loop systems that minimize waste and maximize resource recovery.

12.3 Digital monitoring

Implementing smart sensors and artificial intelligence can enhance process control, early fault detection, and predictive maintenance in AD systems. Real-time monitoring can optimize microbial health, methane production, and energy balance.

12.4 Decentralized and Scalable Systems

Developing modular, small-to-medium scale digesters can support localized food waste management, especially in urban areas, commercial kitchens, hotels and institutions. Decentralization reduces transportation emissions and increases community engagement.

12.5 Policy and incentive frameworks

Governments should implement supportive regulations, feed-in tariffs for biogas, and subsidies for AD infrastructure. Clear and complete food waste collection mandates and standardized organic waste segregation can greatly enhance feedstock quality and system viability.

12.6 Public awareness and stakeholder engagement

Future efforts must involve educating the public and businesses about the importance of food waste separation and the benefits of AD. Collaboration with stakeholders—waste managers, farmers, energy providers—will be essential to scale AD adoption effectively.

12.7 Life cycle and sustainability assessments

More comprehensive life cycle assessments (LCAs) should be conducted to evaluate the long-term environmental and economic benefits of AD systems under varying conditions, ensuring that they align with climate goals and sustainability metrics.

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Author contribution

Arshit Raj: Writing original draft and conceptualization**, Pooja Adwani:** Writing and editing the draft**, Jiwan Singh:** Manuscript validation and correction**, Kondusamy Dhamodharan:** Formal analysis of review.

Conflict of interest

Authors have no conflict of interest.

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