Investigation on Waste to Biogas Conversion: A Comprehensive Review

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Abstract- Biogas, a biofuel rich in energy content, primarily comprises methane. It serves as a sustainable alternative to natural gas or liquefied petroleum gas, offering considerable potential as a renewable energy source. Biogas mainly consists of methane (CH_4) (50–75%), carbon dioxide (CO_2) (25–50%), hydrogen sulfides (H_2S), hydrogen (H_2), ammonia (NH_3) (1–2%), and traces of other gases such as oxygen (O_2) and nitrogen (N_2). Methane holds the potential to substitute fossil fuels across diverse applications, including heat and power generation, as well as within the transportation sector. It can be produced by the anaerobic digestion of various organic wastes. Anaerobic digestion of organic waste has garnered global recognition for its capacity to mitigate greenhouse gas emissions, decrease reliance on fossil fuel combustion, and support the development of a sustainable renewable energy infrastructure. Organic waste stands out as an ideal substrate for anaerobic digestion, owing to its exceptional biodegradability and elevated water content. Research has shown that anaerobic digestion, which converts organic waste into biogas, is a highly effective method for waste management. This process offers numerous benefits, including the reduction of pathogens and the prevention of odor emissions, thereby addressing key challenges associated with waste treatment. The most influential parameters on biogas production include feedstock characteristics (nutrient contents, particle size, and inhibitory compounds), and Factors influencing the anaerobic digestion process include process configuration, pH levels, temperature, retention time, organic loading rate, agitation, hydrogen concentration, moisture content, and the type of inoculum used. These parameters play crucial roles in determining the efficiency and effectiveness of biogas production from organic waste. Challenges and future perspectives on biogas production from various organic wastes are also discussed to improve the performance of anaerobic digestion technology.

Keywords: Biogas; Methane; Anaerobic digestion; Food waste

1. INTRODUCTION

Anaerobic fermentation of organic matter is a technology that is becoming more and more popular every day for the production of biogas. This progress can be attributed to its capacity to alleviate two common issues that humans face in their daily lives. These are the issues of how to obtain energy in appropriate quantities for heating, cooling, lighting, and operating machines, and the other problem is how to dispose of trash properly so as to avoid harming people or the environment. Energy sources are classified as either renewable or non-renewable, with biogas falling under the former category (Shen et al., 2015). Materials originating from plants and animals are classified as organic waste. They include things like stems, leaves, twigs, roots, hair, feathers and blood that are the leftovers of dead plants and animals, in addition to animal waste such as manure. They are described as biodegradable, meaning that microorganisms can break them down into smaller molecules like ammonia, carbon dioxide, and nitrides (Ignatowicz et al., 2023). Biogas is the gas that is obtained when organic matter breaks down in the absence of oxygen, as defined by (Poschinger et al., 2009) . Biogas is derived from biomass (plant and animal remains), and it's produced by anaerobic microorganisms interacting with organic matter. Organic matter is metabolized by enzymes, which reduce large molecules like carbohydrates, proteins, and fats into smaller ones (Okonkwo et al., 2018). The main reason why biogas is important is the presence of methane, which accounts for 45-80% of the gas. The process of anaerobic decomposition of vegetable matter in swampy land produces marsh gas, which is also known as methane gas. According to (Himanen & Hänninen, 2011), plants typically create gas with a higher concentration of carbon (IV) oxide, so the composition of the gas depends on the type of material used. Biodegradable waste can be treated with or without air circulation. The aerobic process is called composting, and the anaerobic process is called digestion. Anaerobic digesters are containers or enclosures that have limited oxygen and a gas outlet. The decomposition of organic matter is carried out in an environment with artificially low oxygen levels during the digestion of organic matter. Anaerobically, biogas exits the gas outlet provided on the digester (Atelge et al., 2020). Most of the organic waste from the soil contains up to 90% moisture; therefore, incineration cannot be applied. Yielding methane-rich biogas for renewable energy production and use. Composting is a simple, fast, and low-cost process for producing compost and CO_2. Digestion is a slower and more sensitive process for selected organic waste materials. In recent years, anaerobic digestion has become the prevailing choice for sustainable organic waste treatment all over the world (Phillipson et al., 1981). Biogas is considered a biofuel, and its production can be constant, provided there is continuous production of waste. Biogas is deemed carbon-neutral because the carbon in it is derived from organic matter, which is deflected from the carbon in the atmosphere (Lima et al., 2023). Biogas can be used for other purposes besides electricity generation, such as domestic heating, vehicle fuel, cogeneration of electricity, and cogeneration of electricity (Ebeya et al., 2022).

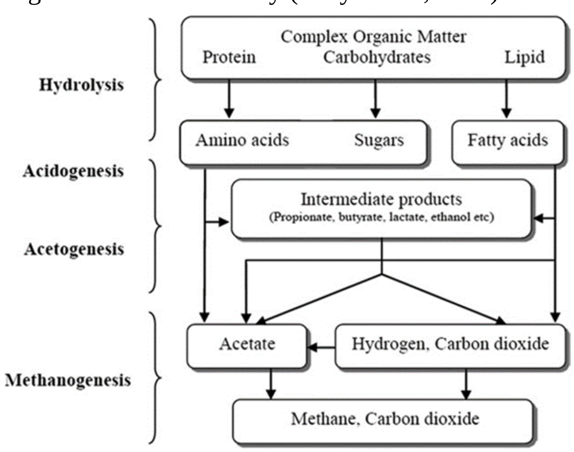

Figure 1: Stages of anaerobic digestion (Jewitt et al., 2009)

Biogas production from livestock:

The livestock sector in India is among the largest globally (Sharma et al., 2022). The combined number of livestock and poultry in the nation is around 535.78 million and 835 million, respectively. The population distribution among different animals includes cows, sheep, goats, buffalo, pigs and equines, all of which can produce dung. Throughout the country, the widespread and abundant availability of cattle dung makes it the primary source for biogas production. Biogas production using various fermented materials through a small-scale model biogas plant. A fixed batch-type dome biogas plant model has been designed and constructed with the aim of generating biogas in the range of 0.5 to 1.0. Biogas generated from fermented materials, including cow dung and poultry waste, was analyzed and compared in the study. The observed biogas production from cow dung and poultry waste was 0.034 m^3/kg and 0.058 m^3/kg respectively. The waste produced by domestic animals is an excellent raw material for biogas production. Poultry waste reached its maximum gas production of 0.026 m^3 on the 8^{th} day, while cow dung achieved a slightly higher maximum gas production of 0.0263 m^3 on the 26^{th} day (D. & Grilc, 2012).

Compare the viability of biogas production from poultry waste alone and a mixture of poultry and fish waste. Fish waste contains a good source of a high level of organic carbon, which is valuable for methane production, as well as a high content of ammonia nitrogen. The biogas extracted from poultry waste exceeds that obtained from poultry droppings. The methane content percentage in various fermented materials is approximately similar (Noorollahi et al., 2015).

In this study, poultry waste and cow dung were co-digested in a ratio of 3:2, supplemented with a mixture of fish waste. All three substrates were co-digested in the ratio of 2:2:1.

Investigate the kinetics of biogas production from agricultural wastes inoculated with cow dung and poultry dropping under mesophilic conditions, with 8% solids content and a retention time of 55 days. A modified first-order kinetic model was developed to characterize the digestion process. A plot of 1/t (ln (dyt/dt)) against 1/t, representing the rate of substrate biodegradability and the removal of the biodegradable fraction of the substrate, was conducted. The findings indicate that maize cobs (MC) possess the highest biodegradable short term index at 1.5827, whereas the biodigester of sugarcane bagasse (SB) exhibits the lowest rate of biodegradable fraction (K) at 0.302 among all the substrates tested. In this experiment, biogas production was compared using water displacement as the method of measurement. The digester had a capacity of 20 liters, and various ratios of waste were fed into the digester for the experiment. Biogas was collected in a water bottle containing a Braine solution of sodium hydroxide, and the increase in the solution level served as an indicator of the amount of biogas produced through anaerobic digestion. After 2 weeks of digestion, the results indicated a significant rise in the Braine solution level, suggesting that biogas production was notably high in the mixture of poultry waste, cow dung, and fish waste (Sharma et al., 2022).

Biogas production from crops and agriculture residues:

Agriculture residues are abundant in bioactive compounds, making them valuable as alternative sources for various applications such as biogas and biofuel production, as well as mushroom cultivation. These residues serve as crucial a raw material in numerous research and industrial endeavors. Crops and agriculture residues encompass a wide array of materials, including leaves, stalks, seed pods, molasses, husks, bagasse, seeds, stems, straw, shells, pulp, stubble, peels, roots, and more. Utilizing agricultural waste as raw material in industries can lead to reduced production costs and lower environmental pollution. Various microorganisms play a crucial role in converting agroindustrial waste into valuable products such as biogas, biofuel, enzymes, animal feed, and other chemicals.

Table 1:Biogas value for different types of fuels (Bhagat et al., 2021)

S. No.	Fuel	Replacement Value	Estimated Equivalent with 15083 Mm^3 of biogas/annum (in millions)
1	LPG	0.45 Kg	6787.35 Kg
2	Firewood	3.47 Kg	52338.01 Kg
3	Cattle dung cake	12.30 Kg	185520.9 Kg
4	Charcoal	1.4 Kg	21116.2 Kg
5	Diesel	0.52 liter	7843.16 liter
6	Electricity	6.5KWh	98039.5KWh
7	Kerosene	0.62 liter	9351.46 liter
8	Gasoline	0.8 liter	12066.4 liter

Explore the vital role of biogas as an alternative energy source. A survey was conducted to determine the quantity of biogas generated from different feedstocks. In a specific laboratory-scale experiment, a mixture of pineapple, plantain, and cassava peelings was utilized as the feedstock to investigate the impact of alkalinity (NaOH) on the volume of biogas production using agriculture waste. The results indicate that the operational conditions inside the digester were maintained at a moderately alkaline level when a high volume of gas was generated. Further results reveal that throughout the experimental period, the temperature within the digester remained within the range of 27 to 35.5°C (Onthong & Juntarachat, 2017).

Generation potential of three distinct cotton wastes, namely cotton stalks, cotton seed hulls, and cotton oil cake, through a batch reactor experiment. For this purpose, biochemical methane potential (BMP) experiments were conducted using two different waste concentrations: 30 g/l and 60 g/l. The findings indicated that cotton waste can be effectively treated anaerobically and serve as a promising source of biogas. Specifically, approximately 65 ml, 86 ml, and 78 ml of CH_4 were produced within 23 days from 1g of cotton stalks, cotton seed hulls, and cotton oil cake, respectively, in the presence of basal medium (BM). The supplementation of BM has a significant positive impact on biogas production (Isci & Demirer, 2007).

Experiments on biogas generation from rice husk waste using the solid state anaerobic digestion (SSAD) method at the laboratory scale (Meggyes & Nagy, 2012).

Enhancing biogas production through preliminary treatments involving physical, chemical, and biological methods for delignification. Various experiments aimed to expedite the fermentation process within the reactor using microorganisms. This method is particularly effective for agriculture waste, particularly rise husk, due to its high total solid content, which leads to reduced water requirements. Solid state anaerobic digestion (SSAD) was found to be capable of producing more biogas compared to liquid anaerobic digestion (Obaideen et al., 2022).

Degradation process of organic matter on two separate substrates: biodegradable waste sourced from landfills and sludge extracted from a wastewater treatment plant using a natural lagoon. These experiments were conducted in a sealed digester with a capacity of one liter. The biogas generated from the anaerobic digestion of both substrates exhibits flammability, with a methane (CH_4) content exceeding 64%. Upon comparing the volume of biogas produced during the digestion of the two substrates, it was observed that the volume collected from the sludge waste exceeded that from organic matter in the landfill by more than 10 times. The volume of biogas produced is inherently determined by the residence time of digestion and the concentration of organic matter in the experiment. Additionally, the percentage decrease in chemical oxygen demand (COD) was estimated at 87.3% for the sludge substrate and 82.44% for the landfill substrate (Laskri & Nedjah, 2015).

Biogas production in eleven rural in Poland. They analyzed the capacity of each plant to generate 500 kW or more of electricity through the supply and processing of organic agro-food waste mixed with silage. Numerous barriers hinder the development of biogas installations, including a lack of political support and investor interest. Additionally, obtaining permission for plant installation is impeded by the administrative burden of mandatory procedures, which persists not only in the development of biogas plants but also in other renewable energy sources. The quantity of biogas can be increased by placing greater emphasis on the management of agricultural waste such as spent wash or potato pulp. This involves implementing effective pre-treatment and saccharification processes, which can be achieved through thorough research and a strategic work plan (Keerthana Devi et al., 2022).

Biogas production from food waste:

Food waste such as leftover vegetables, cooked and uncooked food, used tea leaves, surplus milk, and dairy products can all be utilized as inputs for a biogas digester. Food waste stands out as an ideal substrate for anaerobic fermentation compared to other types of waste. It possesses high energy content and warrants thorough exploration as the primary raw material for biogas production.

Food waste emerges as the optimal choice for biogas generation in community-level biogas plants. This process occurs through the bacterial decomposition of organic matter in an oxygen-deprived environment. Biogas typically comprises approximately 55% to 65% methane and 30% to 40% carbon dioxide. With its considerable calorific value of approximately 4700 kcal or 20 MJ and around 55% methane content, biogas emerges as a valuable energy source. Following the removal of water and the purification of the gas, it can efficiently fuel a power generation system based on biogas. Furthermore, the slurry generated during this process serves as a valuable organic fertilizer, enriching soil fertility and supporting agricultural sustainability. This study aims to assess the effectiveness of various ratios of food waste in a portable floating-type biogas plant made of metal, with a volume capacity of 0.018 m^3, under the outdoor climatic conditions of New Delhi, India. Each biogas plant operates on a batch system with a slurry capacity of 30 kg for all measurements (Agrahari & Tiwari, 2013).

Biogas represents a significant renewable energy resource, comprising 55% methane, and offers a sustainable means of waste management. Notably, it is not restricted by geographical constraints and does not necessitate advanced technology for energy production. Its simplicity of use and application are evident, yet it has not fully realized its potential. The integration of these resources, along with innovative conversion technologies and suitable energy policies, has the potential to elevate biogas as a significant player in the renewable energy arena. Biogas stands to facilitate the decentralization of energy generation, offering immediate cost savings compared to the use of kerosene or LPG for cooking through a compact biogas system. Biogas systems designed for food waste exhibit remarkable efficiency, being approximately 800 times more efficient than conventional biogas systems. The high calorific and nutritive value of food waste enhances microbial activity, thereby significantly increasing methane production efficiency by several orders of magnitude (C.D.K.Reddemma et al., 2023).

The production of biogas was conducted using a modified ARTI model compact biogas plant with a 1 m^3 digester and a 0.75 m gasholder, aiming to manage the daily biodegradable waste produced by households. The biogas produced reached a maximum methane content of 65% and an average maximum carbon dioxide content of 58%. The temperature within the digester ranged from 25°C to 34°C, while the pH value of the slurry ranged between 6.7 and 5.48. On average, 173 L of gas was produced daily, with a maximum burning period of approximately 62 minutes per day and an average burning period of 26 minutes per day. Initially, the proportion of carbon dioxide exceeded that of methane, but over time, methane gradually surpassed carbon dioxide, reaching an average of 56%. Gas production rates were lower in July due to the rainy season but increased thereafter. With a daily feeding of 5 kg of dry food waste producing 173 L of gas per day, each kilogram of food waste could generate 35 L of gas daily. Overall, the system offers an efficient solution for managing food waste while recovering energy from it (Naik, 2019).

Biogas production from waste water:

The quest for affordable and clean energy sourced sustainably is a pressing global challenge. Tackling this issue has triggered a fundamental shift across various sectors, notably organic waste management. The traditional perception of waste as something to dispose of has become obsolete. In the framework of a circular economy, organic waste is viewed as a valuable resource for both energy and nutrient reclamation. It's remarkable that carbon, nitrogen, phosphorus, and energy can be efficiently and economically recovered from organic waste streams such as food scraps and sewage sludge. A promising trend on a global scale involves the valorization of urban organic waste through anaerobic co-digestion (AcoD), leveraging the excess capacity of wastewater treatment plants (WWTPs) (Berktay & Nas, 2008).

AcoD has proven to significantly boost biogas production, outperforming digestion of sewage sludge alone by 2.5 to 4 times (Nayono et al., 2010). This approach has transformed several wastewater treatment plants (WWTPs) into net energy generators.

Raw biogas typically comprises approximately 65% CH_4, 35% CO_2, and trace amounts of hydrogen sulfide, water vapor, ammonia, and siloxane, which can vary based on feedstock and digestion methods (Achinas, Achinas, & Euverink, 2017). However, the presence of CO_2 and other trace gases diminishes the economic value of biogas and restricts its beneficial applications. Therefore, pretreatment is essential to eliminate hydrogen sulfide, water vapor, and other trace gases before optimal utilization. Moreover, for high-value applications like transport fuel or injection into the natural gas grid, complete removal of CO_2 is necessary for methane production, a process known as biogas upgrading.

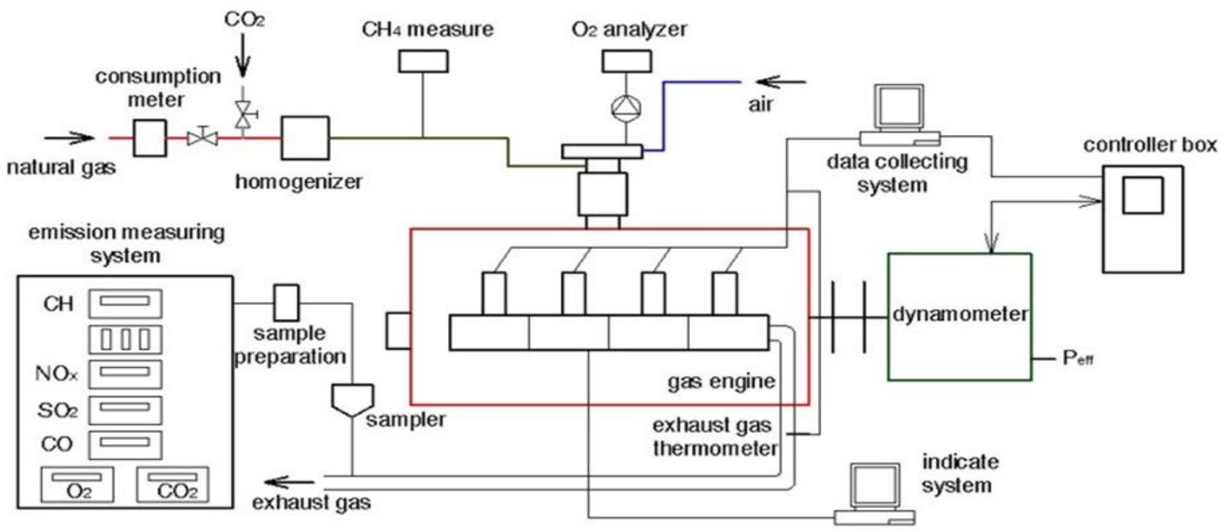

Figure 2: Machine set-up (Meggyes & Nagy, 2009)

Various biogas upgrading technologies exist for commercial applications, including water or organic physical scrubbing, chemical scrubbing, pressure swing adsorption, membrane separation, and cryogenic technology. However, these processes can be highly energy-intensive. The choice of pretreatment and upgrading technologies depends on factors such as biogas composition, available resources, and the desired quality of the final product.

CONCLUSION

This paper focuses on the biogas production that can be combining with the AcoD process at WWTPs to leverage existing infrastructure. The emphasis on pre-treatment and upgrading technologies stems from their crucial role in enabling the beneficial utilization of produced biogas. Beyond facilitating the efficient use of biogas, these techniques offer additional benefits that warrant attention. Through a critical review, this examination aims to provide guidance for practitioners, water engineers, and scientists involved in future sustainable development efforts (Achinas, Achinas, Euverink, et al., 2017). By exploring the emerging benefits of these technologies, this review seeks to inform and inspire innovative approaches toward more sustainable biogas production and utilization practices.

AcoD at WWTPs involves the digestion of sewage sludge along with one or more co-substrates characterized by high organic content. These co-substrates typically include essential organic wastes such as food and kitchen waste, the organic fraction of municipal solid waste (OFMSW), fat oil and grease (FOG), waste from food and beverage processing, as well as by-products from biofuel production such as crude glycerol, microalgae, and corn silage. The underlying theoretical principle of AcoD lies in the synergy between nutrient-rich sewage sludge and carbon-rich organic wastes. This complementary relationship enables optimal biogas production and nutrient recovery, facilitating a more efficient and sustainable waste management process.

Raw biogas typically consists of approximately 65% CH_4 and 35% CO_2 (Bachmann, 2015). The energy content of biogas is primarily determined by its methane concentration-the higher the methane content, the greater the calorific energy value of the gas. For instance, biogas with a methane concentration of 70% has a calorific value (measured by the Wobbe index) of 21.5 MJ/Nm^3, whereas methane with 100% methane content has a calorific value of 35.8 MJ/Nm^3. The significant proportion of CO_2 in biogas not only diminishes its calorific value but also renders it economically unviable for certain applications.

Once pre-treated, biogas can undergo further processing to remove CO_2 and produce methane. Various biogas upgrading methods are already commercially available, including scrubbing (using water, organic solvents, or chemical agents), pressure swing adsorption, membrane separation, and cryogenic technology. However, the maturity level of these methods varies considerably. It's important to note that certain biogas upgrading methods can also remove impurities, particularly hydrogen sulfide (H_2S). Water scrubbing (utilizing water as the scrubbing medium) can effectively eliminate H_2S along with CO_2, contributing to the overall purification of the biogas stream.

Through the anaerobic co-digestion of sewage sludge and organic waste, numerous wastewater treatment plants (WWTPs) globally have attained energy self-sufficiency and generated surplus biogas. Leveraging biogas upgrading to methane, attractive applications such as natural gas grid injection and transport fuels emerge as viable options to utilize this surplus biogas. Biogas upgrading technologies, encompassing water, organic, and chemical scrubbing, pressure swing adsorption, membrane separation, and cryogenic methods, are readily available on a commercial scale (Bhushan & Nayak, 2022). These technologies play a pivotal role in enhancing the quality and value of biogas, enabling its integration into diverse energy systems and transportation networks.

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