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Design and Development of a Modified Biogas Digester for Energy Generation through Domestic Waste

Dr. Amey S. Wagh[1], Naresh Anabathula[2], Saud Sakharkar[3], Anas Shaikh Sharif[4]

[1]Asstt. Professor, Dept. of Mech. Engineering, M.H. Saboo Siddik College of Engineering, Mumbai, 400008, India.
[2,3,4]G- student, Dept. of Mech. Engineering, M.H. Saboo Siddik College of Engineering, Mumbai, 400008, India.

*Corresponding author: **amey.wagh@mhsscoe.ac.in**, 0009-0002-6797-9105*

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***Abstract** - Biogas production from kitchen waste presents a sustainable and eco-friendly solution for energy generation while addressing the challenges of waste disposal. This study explores the anaerobic digestion process, factors affecting biogas yield, technological advancements, and the potential of kitchen waste as an effective feedstock. The findings confirm that kitchen waste, with its high organic content, is an excellent substrate for biogas production. The study also examines the challenges related to feedstock composition, microbial activity, and process optimization. It emphasizes the advantages of using kitchen waste in urban environments, including reducing costs for cooking gas and electricity. By utilizing kitchen waste for biogas production, urban communities can decrease their reliance on fossil fuels, lower greenhouse gas emissions, and establish more sustainable waste management systems.*

***Keywords-** Biogas yield, Kitchen waste, Portable Digester, Waste management*

INTRODUCTION

The growing need for sustainable energy has driven the exploration of renewable energy sources. Biogas is a promising renewable technology with the potential to transform animal, agricultural, municipal, and industrial waste into a clean, non-polluting energy source. Biogas is a blend of gases; primarily methane, carbon dioxide, traces of hydrogen sulfide, and moisture-generated through the anaerobic digestion of biodegradable organic materials [1]. Kitchen waste, being a plentiful source of biodegradable organic material, offers great potential for effective biogas production via anaerobic digestion.

When kitchen waste breaks down in the absence of oxygen, it produces a mixture of methane and carbon dioxide that can be utilized as a renewable energy source. With increasing generation of kitchen waste globally, harnessing its energy potential through biogas production can contribute significantly to sustainable energy development, waste management, and environmental sustainability. This highlights the importance of exploring efficient biogas production technologies using kitchen waste.

Biomass is a renewable energy source and thus reduces dependency on fossil fuels and minimizes landfill accumulation. Low-cost fuel production Reduces methane emissions from decomposing organic waste. When the anaerobic digestion (AD) feed consists of animal manure and/or agricultural residues, the resulting digestate can be effectively reused on farms as a fertilizer. Digestate produced from the organic fraction of solid municipal waste (OFSMW) is subject to much stricter regulations [2].

Different feed waste feedstock including food waste can be adopted as feedstock with considerable methane generation [3]. The adoption of bio-digesters is anticipated to improve air quality, particularly in kitchens, by promoting the use of biogas stoves and reducing reliance on wood stoves, which are known for emitting biomass particulates [4]. A specific methanogenic bacterium acclimated to the substrate demonstrates superior methane production performance compared to commercial activators [5].

LITERATURE REVIEW

A key objective of this research was to assess the performance of the anaerobic digestion process under varying loading rates. To achieve this, it was essential to evaluate the process based on biogas production and degradation rates [6].

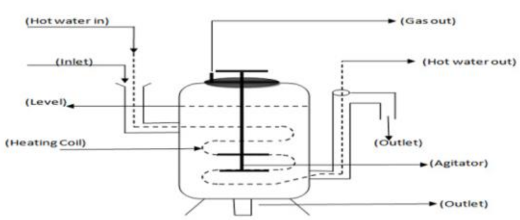

Fig 1- A portable biogas setup [6].

This study aimed to explore the conversion of food waste into biogas and to design an anaerobic digester capable of utilizing food waste for biogas generation. Kitchen waste such as vegetable scraps, leftover cooked and uncooked food, as well as discarded milk and dairy products, can all be processed in this system [7]. A household-level biogas unit designed to process kitchen waste has been proposed to be compact enough for easy installation in homes and hotels, particularly for urban apartment dwellers [8]. A biogas plant utilizing municipal waste presents a promising approach to mitigating urban smog. Equipping the plant with methane storage tanks is also essential to store the generated energy efficiently [9]. The development of a portable digester, designed with economic and ergonomic considerations for maximum methane production efficiency in all weather conditions, demonstrated two key benefits for society: reducing waste and providing valuable energy [10].

In many cities and regions, food waste is either sent to landfills or improperly discarded, causing public health risks and diseases such as malaria and cholera. Inadequate waste management, like uncontrolled dumping, leads to various negative consequences. Anaerobic digestion offers several environmental benefits, such as the production of green energy and natural fertilizers [11]. The rapid biodegradation of organic waste is essential for processing it in a more environmentally responsible way, as opposed to relying on landfilling or composting [12]. Solid waste from residential areas, along with waste from food processing, commercial, and agricultural activities, contains significant amounts of biodegradable organic matter [13].

Raw materials for biogas production can include animal manure, plant matter (such as green mass), corn silage, expired food products (if hygienically safe), spoiled seeds, turnip noodles, molasses, fruit pulp, residues from fruit and vegetable processing, seeds, bark, fallen fruit, food scraps, and by-products from industries like beer, milk and cheese production, and oil production [14].

The fundamental process of biogas production generally consists of the following stages:

1. Preparation of raw materials for processing;
2. Anaerobic digestion;
3. Storage, transportation, and utilization of the resulting liquid;
4. Storage, purification, and utilization of the biogas.

Wet waste is typically converted into fertilizer, methane gas, or a combination of both, while dry waste can be reused or repurposed. Although there are many advanced technologies for waste separation, it is always more effective to separate waste at the source. The benefits of doing so include higher quality materials for recycling, which results in a greater

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recovery of value from the waste [15]. Biogas is a renewable energy source generated through the anaerobic digestion (AD) of organic matter, in which the organic material is transformed into combustible biogas, primarily composed of methane (CH4), along with liquid effluents [16].

Temperature plays a crucial role in the degradation process, as higher temperatures can accelerate the degradation rate, thereby increasing the gas production rate [17]. Biomass sources, including agricultural waste, municipal waste, and green waste (such as kitchen waste), present a promising opportunity for renewable energy production [18].

Ultrasonication is a mechanical pretreatment technique applied to substrates before hydrolysis. It involves generating significant hydro-mechanical shear forces from cavitation bubbles formed by high-intensity ultrasonic waves, which is considered the primary factor in sludge disintegration. Food waste treated with ultrasound has been found to produce more biogas compared to treatments using autoclaves or microwaves [19].

Kitchen and garden waste (KGW) are heterogeneous, containing a variety of biodegradable components with differing properties. These wastes include easily convertible carbohydrates, such as starchy compounds, as well as more resistant materials like lignocelluloses. Lignocellulosic substances are primarily composed of carbohydrates (including cellulose and hemicellulose), lignin, and other non-carbohydrate materials. To efficiently convert lignocellulosic carbohydrates into biofuels, a pretreatment process is necessary. One of the most effective and commonly used methods for processing lignocellulosic materials is dilute sulfuric acid pretreatment [20].

Anaerobic digestion (AD) systems require substantial capital investment, and their economic viability largely depends on the revenue generated from biogas, solids, and liquid effluent. Food waste, with its high energy content, can significantly enhance biogas yield in AD systems [21]. During the process, protein concentrations gradually decrease, while pretreated kitchen waste (KW) shows higher crude protein content in the liquid phase [22]. Low-cost household digesters present a promising technology to help reduce environmental pressures caused by deforestation and greenhouse gas emissions [23].

The slurry produced after biogas generation can be converted into organic fertilizers, which can be sold to generate income for institutions such as the Kitchen Training Technical Institute (KTTI) [24]. One of the key benefits of the anaerobic digestion process is that the resulting product can be used as vehicle fuel or for combined electricity and heat generation. Kitchen waste (KW) is an easily biodegradable organic material, rich in moisture, carbohydrates, lipids, and proteins [25]. Utilizing KW to produce value-added products through enzymatic reactions holds potential for enhancing the food supply chain and improving food security [26].

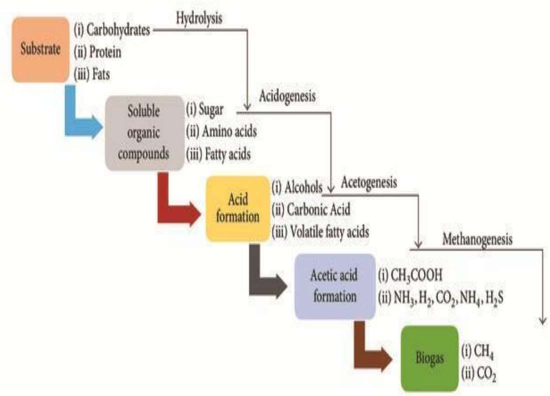

Fig2- Anaerobic digestion phases [27].

Anaerobic digestion takes place in the absence of oxygen, breaking down organic materials into biogas, trace amounts of other gases, and stabilizing the digestion process [27]. The energy efficiency of anaerobic digestion can be enhanced through physical, chemical, or biological pre-treatment processes that increase the hydrolysis rate [28].

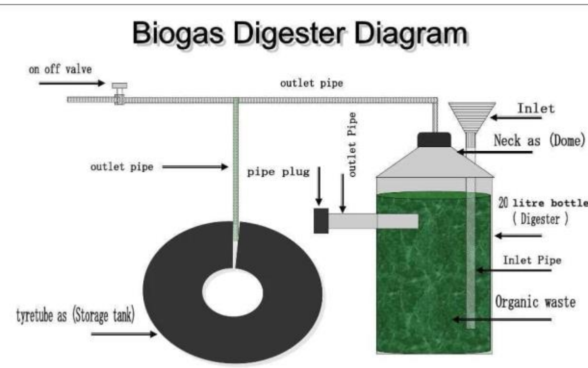

Fig 3- Biogas plant digester diagram [29].

The gas generation directly depends on the initial characteristics of the substrates. The results indicate that the food waste is the best source of methane generation due to its biodegradable capacity Biogas production from different food wastes could be enhanced by adopting biotechnological applications [30]. The application of ML in AD has mainly focused on the prediction of biogas yield and composition, monitor process stability, and optimize process parameters, thereby enhancing the efficiency and quality of AD [31].

METHODOLOGY

1. Feedstock Characterization: Domestic waste samples were collected and characterized to determine their physical and chemical properties, including moisture content, volatile solids, and carbon-to-nitrogen ratio, factors affecting biogas production, etc.
2. Digester Design and Development: Using computer-aided design (CAD) software and on the basis of calculation, a modified biogas digester was designed and developed. The design is supposed to incorporate innovative features such as optimized mixing system, enhanced heat retention, and improved feedstock loading system.
3. Simulation and Modeling: Computational fluid dynamics (CFD) simulations were performed to model the anaerobic digestion process and predict biogas production rates, yields, and composition.
4. Experimental Validation: A laboratory-scale prototype of the modified biogas digester was constructed and tested using domestic waste as feedstock. Biogas production rates, yields, and composition were measured and compared with simulated results.
5. Data Analysis and Optimization: Experimental data were analyzed to identify areas for optimization and improvement. The digester design and operational parameters were optimized to maximize biogas production and efficiency.

Kitchen waste comprises food residues rich in carbohydrates, proteins, and fats, all of which contribute to high biogas yields. Compared to other organic waste like cow dung, kitchen waste has a higher calorific value and biodegradability, making it an ideal substrate.

The digester design features to be incorporated for effective biogas generation:

Optimized Mixing System:

1. Mixing Mechanism: A mechanical mixing system will be designed, consisting of a central shaft with paddles or impellers. This will ensure uniform distribution of feedstock and microorganisms.
2. Mixing Frequency and Duration: The mixing frequency and duration will be optimized based on the feedstock characteristics and digester operating conditions.
3. Baffles and Guides: Baffles and guides will be incorporated to direct the flow of materials and prevent settling or scum formation.

Enhanced Heat Retention:

1. Insulation: The digester will be insulated with a minimum of 50mm of foam insulation or equivalent to minimize heat loss.
2. Heat Exchanger: A heat exchanger will be integrated into the digester design to recover heat from the biogas and transfer it to the digester contents.
3. Temperature Monitoring: Temperature sensors will be installed to monitor the digester temperature and adjust the heating system as needed.

Improved Feedstock Loading System:

1. Feedstock Hopper: A feedstock hopper will be designed to store and meter the feedstock into the digester.
2. Pneumatic or Hydraulic System: A pneumatic or hydraulic system will be used to transfer the feedstock from the hopper to the digester.
3. Feedstock Pre-Treatment: A feedstock pre-treatment system will be incorporated to shred or chop the feedstock into uniform sizes, ensuring efficient digestion.

Digester Shape and Size:

1. Cylindrical Shape: The digester will be designed with a cylindrical shape to provide maximum volume while minimizing surface area.

2. Digester Size: The digester size will be calculated based on the feedstock loading rate, retention time, and biogas production rate.

Materials of Construction:

1. Steel or Concrete: The digester will be constructed from steel or concrete, ensuring durability and resistance to corrosion.
2. Coatings and Linings: The digester interior will be coated or lined with a durable, non-toxic material to prevent corrosion and ensure easy cleaning.

Safety Features:

1. A pressure relief valve will be used to prevent over-pressurization of the digester.
2. Emergency Shutdown System: An emergency shutdown system will be designed to quickly stop the digester operation in case of an emergency.
3. Gas Detection System: A gas detection system will be installed to monitor the biogas composition and detect any potential safety hazards

DESIGN

Different design calculations are performed considering different combinations of scenarios. A program is developed based on modeling biogas digester to calculate biogas production. Calculating

Biogas Production;

Daily biogas production = Daily kitchen waste × Biogas yield

Monthly biogas production = Daily biogas production × 30 days

1. Calculating Digester Volume;

Digester volume = Total biogas production × Time required for biogas production Slurry density

Total biogas production = Daily biogas production × Time required for biogas production

Digester volume = Total biogas production / Slurry density

2. Calculating Methane Output;

Daily methane output = Daily biogas production × Percentage of methane in biogas

methane output = Daily Methane output × 30 days

4. Calculating Energy Output;

Daily energy output = Daily Methane output × Heat of combustion of methane

Monthly energy output = Daily energy output × 30 days.

RESULT & DISCUSSION

The study found that the small-scale household biogas plant produces 0.125 m³ of biogas daily, requiring a digester volume of 2.5 m³. It generates 0.09375 m³ of methane per day, corresponding to an energy output of 2.625 MJ, equivalent to 0.73 kg of LPG. This highlights the feasibility of using small-scale biogas plants to produce energy from kitchen waste. The compact digester volume makes it suitable for household use, with potential for scaling up in urban areas. Additionally, the remaining feedstock can be repurposed as fertilizer for crops or plants.

CONCLUSION

In conclusion, small-scale household biogas plants offer significant potential for effectively managing kitchen waste while producing biogas for cooking. The findings of this study demonstrate the practicality and efficiency of these systems in converting organic waste into a valuable renewable energy source.
This study highlights the promise of small-scale biogas plants in addressing waste and promoting sustainable energy production. Although further research is necessary to accelerate the adoption of this technology, the results provide a strong foundation for future advancements.

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