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Study of Biogas Plant for Urban Waste Management

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ABSTRACT: Urban centers are facing a growing challenge in managing the increasing volumes of organic waste in a sustainable and cost-effective manner. This study presents the design and implementation of a smart biogas plant integrated with urban waste management systems, aimed at converting biodegradable municipal solid waste into renewable energy. A biogas plant is a facility where organic waste such as animal dung, food waste, crop residues and sewage is decomposed anaerobically (in the absence of oxygen) by microorganisms to produce biogas (mainly methane and carbon dioxide). This biogas can be used for cooking, electricity generation and heating. This study represents the design, implementation and operational analysis of a biogas plant aimed at producing renewable energy from organic waste materials. The primary objective of the plant is to convert biodegradable waste, such as food scraps or kitchen waste into biogas through anaerobic digestion. The biogas produced is a mixture of methane and carbon dioxide, which can be utilized for electricity generation, heating and as a replacement for conventional fossil fuels. The rapid urbanization and increasing generation of organic municipal waste have necessitated the development of sustainable and intelligent waste management solutions. This report indicate the design, implementation, and performance analysis of a smart biogas plant tailored for urban waste management. The plant utilizes biodegradable urban waste, such as food scraps and organic residues, to produce biogas through anaerobic digestion. The study evaluates the biogas yield, waste processing efficiency, and environmental benefits of the system in an urban context. Results demonstrate that the smart biogas plant not only offers a sustainable alternative to conventional waste disposal methods but also contributes to renewable energy generation and reduction of greenhouse gas emissions.

KEYWORDS: Inlet, Outlet & Digestion Chamber, Gas Holder etc.

I. INTRODUCTION

The programs for promoting biogas technologies have been running since the 1970s in India. The first oil crisis made evident to Indian policymakers that commercial energy would remain outside the economic reach of rural and urban poor. By the late 1970s, traditional local energy resources like agriculture waste, animal waste and fuel-wood were no longer freely available in many rural areas. The biogas development program in 1981 was part of a multi-pronged approach to alleviate the rural energy crisis. Growing concerns towards solid waste management and climate change are key drivers behind policy initiatives to increase biogas development in urban areas. Urban areas are facing increasing challenges in managing the vast quantities of organic waste generated from households, markets, restaurants and institutions. Traditional waste disposal methods such as landfilling and incineration not only pose serious environmental threats but also fail to harness the potential energy contained within biodegradable waste. In light of growing concerns regarding climate change, fossil fuel dependency, and sustainable development, biogas technology has emerged as a promising solution for waste-to-energy conversion. Biogas plants employ anaerobic digestion to break down organic matter, producing a renewable mixture of methane and carbon dioxide that can be used for cooking, heating, electricity generation or even as vehicle fuel. However, conventional biogas plants often suffer from operational inefficiencies, lack of real-time monitoring and poor adaptability to dynamic urban waste patterns.

II. LITERATURE SURVEY

In 2023, Matteo Fedeli and Alessandro di Pretoro, they studied about Conventional vs. alternative biogas utilizations as an LCA-AHP based comparative study. Three different biogas usage methods receive evaluation in this study with combined heat, power cycle (CHP cycle) as well as dimethyl ether production (DME production) and methanol production. Both the processes displayed excellent methane conversion rates of 92.8% in addition to DME production reaching 89% until completion. Significant CO conversion rates of 32.6% emerged from chemical pathways which demonstrates their value as pathways for creating advanced chemicals. The process of CHP generated the lowest global warming potential but DME and methanol production requirements for steam generation along with electricity consumption increased their overall environmental impact. The production of DME represents an attractive solution because it combines good ecological performance with economic sustainability. Effective urban waste management has become a critical challenge due to the rapid pace of urbanization and the corresponding increase in the generation of organic waste. Numerous studies have investigated the role of biogas technology in converting organic waste into renewable energy through anaerobic digestion (AD). Traditional biogas systems, while effective in rural settings, often struggle with scalability, monitoring and operational control in complex urban environments. Several researchers have demonstrated the viability of biogas production from urban organic waste such as food waste, vegetable market residue and slaughterhouse waste. According to Yadvika et al. 2004, the anaerobic digestion process is efficient in reducing the volume of solid waste while generating a renewable source of energy. Studies by Khandelwal and Gupta in 2009, emphasized the environmental benefits of biogas systems, including greenhouse gas reduction and the production of nutrient-rich slurry as a by-product. Several pilot projects and case studies have demonstrated the successful implementation of smart biogas plants in urban areas. For example, the Pune Municipal Corporation in India introduced smart digesters to manage market waste, equipped with GSM-based control systems. Another study by Sharma et al. 2019, demonstrated the use of cloud-based dashboards for monitoring gas production trends and alert generation.

III. METHODOLOGY

Biogas Plant types:

Three main types of simple biogas plants can be distinguished:

1. Balloon plants
2. Fixed-dome plants
3. Floating-drum plants

1. Balloon Plants

A balloon plant consists of a plastic or rubber digester bag, in the upper part of which the gas is stored. The inlet and outlet are attached direct to the skin of the balloon. When the gas space is full, the plant works like a fixed-dome plant - i.e., the balloon is not inflated; it is not very elastic.

The fermentation slurry is agitated slightly by the movement of the balloon skin. This is favourable to the digestion process. Even difficult feed materials, such as water hyacinths can be used in a balloon plant. The balloon material must be UV-resistant. Materials which have been used successfully include RMP (Red Mud Plastic), Trevira and butyl.

2. Fixed-Dome Plants

A fixed-dome plant consists of an enclosed digester with a fixed, non-movable gas space. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the compensating tank. Gas pressure increases with the volume of gas stored. Therefore, the volume of the digester should not exceed 20 m³. If there is little gas in the holder, the gas pressure is low.

- Mixing tank with inlet pipe.
- Digester.
- Compensating and removal tank.
- Gasholder.
- Gas pipe.
- Entry hatch, with gaslight seal and weighted.

- Difference in level = gas pressure in cm WC.
- Supernatant scum; broken up by varying level.
- Accumulation of thick sludge.
- Accumulation of grit and stones.
- Zero line: filling height without gas pressure.

If the gas is required at constant pressure (e.g. for engines), a gas pressure regulator or a floating gasholder is required. Engines require a great deal of gas and hence large gasholders. The gas pressure then becomes too high if there is no floating gasholder.

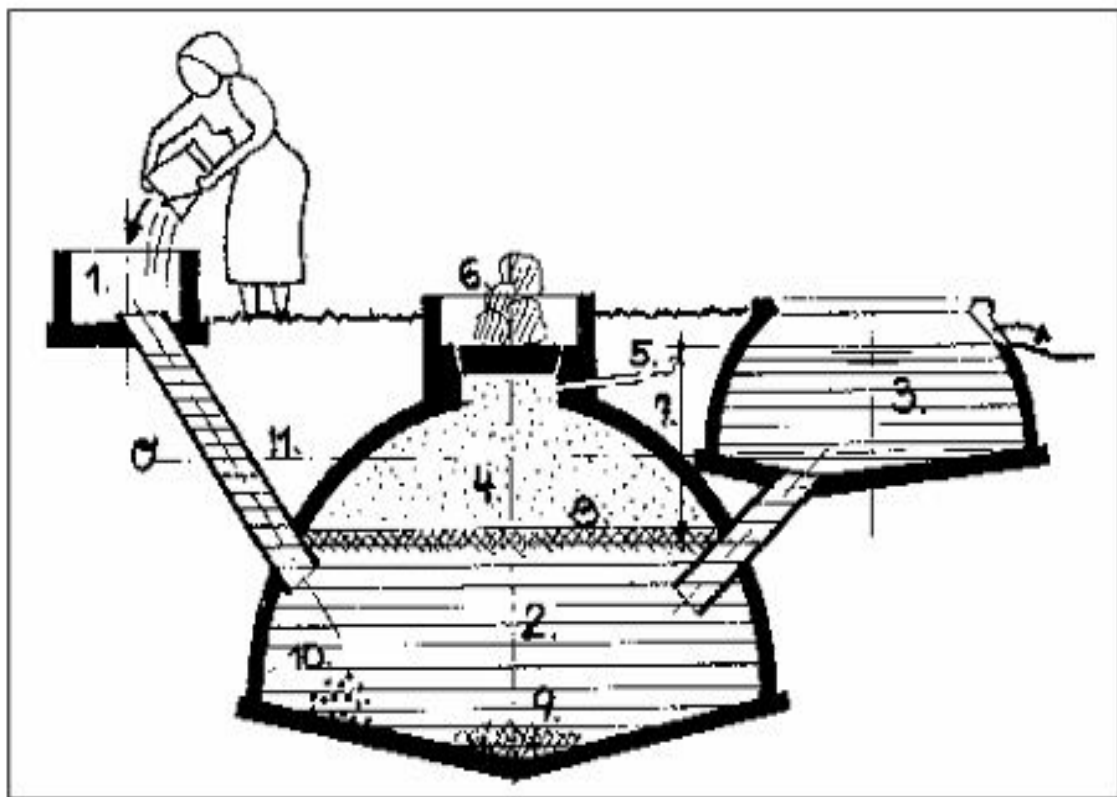


Fig. 1 Fixed-dome plant

3. Floating-Drum Plants

Floating-drum plants consist of a digester and a moving gasholder. The gasholder floats either direct on the fermentation slurry or in a water jacket of its own. The gas collects in the gas drum, which thereby rises. If gas is drawn off, it falls again. The gas drum is prevented from tilting by a guide frame.

- Mixing tank with inlet pipe.
- Digester.
- Overflow on outlet pipe.
- Gasholder with braces for breaking up surface scum.
- Gas outlet with main cock.
- Gas drum guide structure.
- Difference in level = gas pressure in cm WC.
- Floating scum in the case of fibrous feed material.
- Accumulation of thick sludge.

- Accumulation of grit and stones.
- Water jacket with oil film.

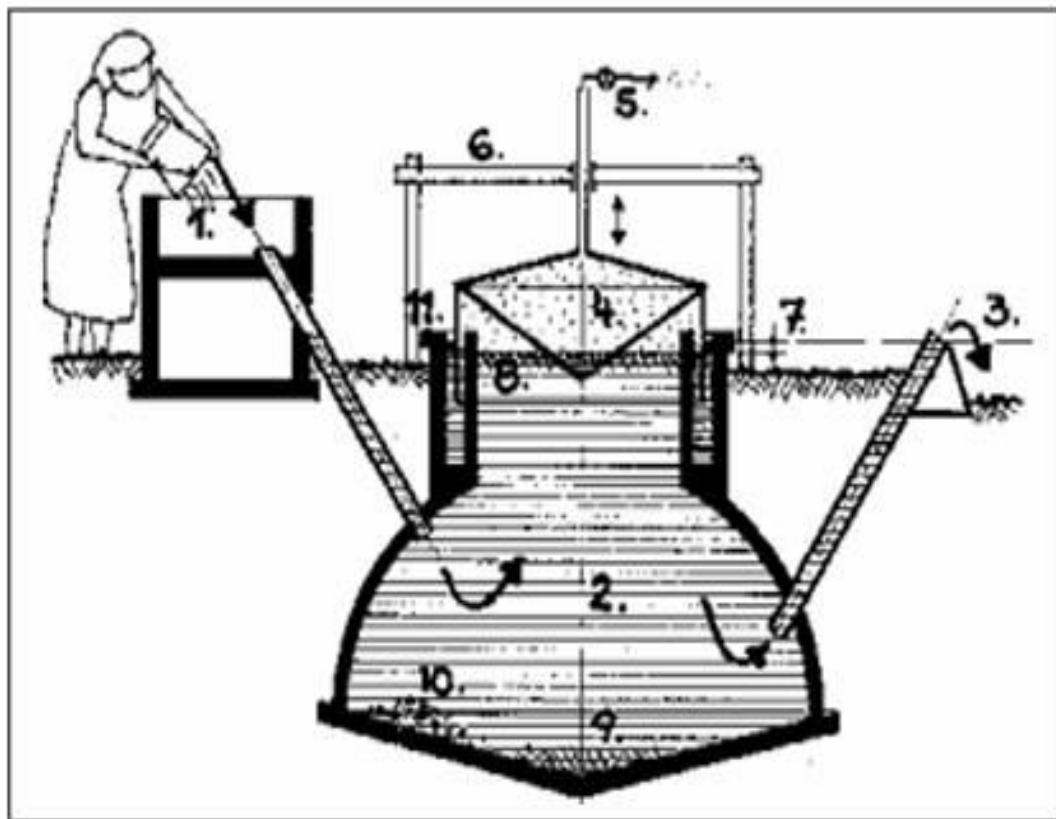


Fig. 2 Floating-drum plant

Advantages:

It's a Renewable Energy Source: The raw materials used in the production of biogas are renewable. Trees and crops will continually grow, which means manure, food scraps, and crop residue will continuously be available.

It's Eco-friendly: Production of biogas happens without oxygen, which technically means there is no form of combustion involved. No combustion means there is zero emission of greenhouse gasses to the atmosphere. While similar to fossil fuel biogas produces carbon dioxide, the amount produced in this biological breakdown process (anaerobic digestion), is far less compared to that produced by fossil fuels. In fact, the amount of carbon dioxide produced when using biogas is equal to the amount needed for plants to grow. This will balance the carbon dioxide in the atmosphere.

Reliable: The fact that it is produced from renewable sources makes it reliable. Other renewable energy sources like solar and wind depend on the weather patterns or day time factors to continually produce electricity. But, that's not the case with biogas. Unlike solar and wind energy generation, producing biogas isn't dependent on the weather. This means that the biogas production process goes on uninterrupted (24/7).

Reduces the Amount of Waste Going to Landfills: We all know that overflowing landfills cause environmental impacts such as foul smells and toxic liquids draining into underground water sources. Instead of disposing of these organic materials in landfills, they can be used to produce biogas. The more waste has to be broken down to produce Biogas, the less amount of waste will eventually have to wind up in landfills.

Requires Low Capital Investment: The technology used to produce biogas is pretty cheap. Biogas plants can be developed right at home using locally sourced materials and the resultant gas is used directly for cooking and the generation of electricity. In addition, biogas can also be compressed to achieve the quality of natural gas and utilized to power automobiles. The raw materials used for the production of biogas such as manure, crop residue, food scraps and wastewater sludge are absolutely free. This makes the cost of biogas production significantly low.

Disadvantages:

Little Technology Advancements: The systems used in the production of biogas today are not efficient. There are no new technologies yet to simplify the process and make it abundant and low-cost. This means large-scale production to satisfy a large population is still not possible. Although the biogas plants available today can meet some energy needs, most individuals and governments are not willing to invest in the sector heavily. This aspect has led many people to put up biomass systems in their homes, which are short on capacity.

Contains Impurities: Biogas still contains impurities even after refining and compression. When utilized as fuel to power automobiles, it can corrode your engines and lead to extraordinary maintenance costs.

It Can't Work in all Locations: Biogas production is only feasible in certain locations where raw materials are in plentiful supply. Rural areas provide the best locations for building biogas plants, while large cities are the most disadvantaged.

Not Economically Viable: Compared to other biofuels, the production of biogas is not attractive economically, especially on a large scale. It's difficult to beef up the efficiency of biogas plants, which explains why people and most governments are coy about investing in this realm.

Biogas Production Is a Temperature-Sensitive Procedure: Biogas production, like the production of energy from other renewable and sustainable resources, is temperature sensitive and is affected by the weather. The bacteria responsible for the production of biogas from the decomposition of organic materials need a specific optimal temperature. The aiding bacteria require an optimal temperature of 37°C to function properly, which sometimes is not easy to maintain.

Applications:

Biogas as a Cooking Fuel:

The renewable and environmentally friendly energy source biogas serves as a rising cooking fuel choice for both rural villages and semi-urban settlements. The anaerobic decomposition of organic materials which includes animal dung, agricultural waste and kitchen leftovers forms biogas.

Use of Biogas as a Lighting Fuel:

Direct usage of low-pressure household gas through specially designed burners specifically yields optimal results when applied to gas mantle lamps for illuminating purposes.

Utilization of Biogas for Pumping Water:

The use of biogas technology for water pumping operations provides a sustainable economical alternative that fits best for rural agricultural areas. The anaerobic digestion process converts livestock manure together with agricultural waste into biogas which powers modified internal combustion motors to run irrigation pumps

Biogas as a Fuel for Running IC Engines:

Biogas obtained from organic material digestion through anaerobic digestion functions as a sustainable fuel source that powers internal combustion engines effectively.

Biogas as a Vehicle Fuel:

Bio methane derived from the upgrade of biogas functions as a sustainable vehicle fuel that offers renewable alternatives to standard fossil fuels.

Applications of Biogas for Power Generation:

Renewable biogas serves as a flexible power generation source because its energy potential works effectively for this purpose. Through anaerobic digestion of organic waste materials including agricultural waste and manure and food scraps biogas forms primarily from methane before it is used to create electricity.

IV. EXPERIMENTAL RESULTS

Compared three different types of biogas plant configurations applied to urban waste management:

1. Balloon plants
2. Fixed Dome Smart Biogas Plant
3. Floating Drum Smart Biogas Plant

The performance was analyzed in terms of gas yield, waste processing efficiency, automation reliability, cost-effectiveness and environmental benefits. The selection of plant is based on user needs, site conditions, climate, budget and waste availability.

- Fixed Dome Plants were most economical per kg of waste but not space-efficient.
- Floating Drum Units balanced cost and performance, suitable for semi-urban or Peri-urban zones.
- Floating Drum Systems required frequent drum cleaning and maintenance.
- Fixed Dome Systems were durable but lacked flexibility in operation and expansion.
- Smart technologies significantly improve the efficiency and manageability of urban biogas plants.
- Floating Drum Plants offer a balance of performance and cost for medium-scale users.
- Fixed Dome Plants are still viable for larger, low-tech community-based operations where space is not a constraint.
- Fixed-dome plants produced the highest volume of gas but had variable pressure depending on the gas quantity.
- Floating-drum plants offered more consistent gas delivery suitable for applications like cooking due to their regulated pressure.
- Balloon plants, while lower in yield, still provided sufficient gas for small households, especially in warmer climates.
- Balloon plants were found to be quickest and cheapest to install, making them ideal for temporary or emergency setups.
- Fixed-dome plants, though costlier and requiring skilled construction, proved long-lasting and suitable for permanent installations.
- Floating-drum plants involved higher maintenance, especially due to the risk of corrosion in the drum, despite offering ease of gas monitoring.
- Balloon plants required care to avoid punctures and UV damage but were highly space-efficient.
- Fixed-dome plants were low-maintenance once constructed but required larger area.
- Floating-drum plants offer a balance between domestic and institutional use, particularly where gas pressure stability is critical.
- Balloon plants are best for low-cost, small-scale and mobile applications.
- Fixed-dome plants are ideal for long-term, low-maintenance, high-capacity use.
- Floating-drum plants provide user-friendly operation and constant gas pressure, making them excellent for urban homes or institutional kitchens.

Table No. 01 Comparison of different types of Smart Biogas Plant.

Sl. No.	Plant Type	Avg. Biogas Yield (m ³ /day)	Methane Content (%)	Gas Pressure Stability
1	Balloon plant	1.0 – 1.2	55 – 60%	Low
2	Fixed Dome Plant	1.3 – 1.5	55 – 60%	Medium (varies with volume)
3	Floating Drum Plant	1.2 – 1.4	60 – 65%	High (Constant Pressure)

V. CONCLUSION

The comparative study of Balloon, Fixed-Dome and Floating-Drum biogas plants highlights that each type serves specific needs based on cost, performance, durability and user requirements. Balloon Plants are low-cost, easy to install and portable, making them highly suitable for small-scale or temporary setups, especially in rural or remote locations. However, they have a shorter lifespan and are more susceptible to damage and climate sensitivity. Fixed-Dome Plants offer a long-lasting and robust solution, ideal for community-level or permanent installations. Their low maintenance needs and underground construction make them energy efficient, but they require skilled labor, more space and higher upfront costs. Floating-Drum Plants provide ease of use, consistent gas pressure and visible gas storage levels, making them user-friendly for domestic or institutional applications. However, they demand regular maintenance due to potential corrosion and moving parts.

Study of different plants shows that no single type is universally superior, rather than optimal choice depends on local conditions, available budget, waste volume and user expectations. For sustainable urban waste management, integrating these biogas systems with smart monitoring technologies (IoT, Sensors, Automation) can significantly enhance their performance, safety and usability which may bridges the gap between traditional biogas models and modern urban needs.

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