# Optimisation Of A Biogas Plant For Enhanced Biogas Production And Methane Concentration

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***Abstract-*** *An increase in the world's demand for renewable/sustainable sources of energy has created significant interest in the environmental benefits of producing biogas from organic waste for both energy production and managing organic waste on a distributed basis. The traditional biogas plants exhibit a number of problems – including low concentrations of methane, instability in the digestion process, poor feedstock management, and lack of effective systems to purify gas produced – all of which lower the combustion efficiency and energy output of the plant. In this article, the authors provide a conceptual framework for designing and optimising a smart biogas plant to improve yields and quality of biogas produced.*

*The proposed system integrates multiple optimisation strategies, including feedstock balancing through controlled carbon-to-nitrogen (C:N) ratio management, mechanical and thermal pretreatment of biomass, mesophilic temperature regulation using insulation and solar-assisted heating, controlled mixing mechanisms, and low-cost biogas purification techniques for the removal of carbon dioxide, hydrogen sulfide, and moisture. In addition, the incorporation of temperature sensors and automated control systems is proposed to maintain stable anaerobic digestion conditions and improve process efficiency.*

*Theoretical analysis and findings from existing literature indicate that the integrated optimisation approach can significantly improve digestion stability, methane concentration, calorific value, and biogas purity compared to conventional biogas systems. Furthermore, the proposed model offers potential benefits in terms of renewable energy generation, waste utilisation, environmental sustainability, and reduced greenhouse gas emissions. The study provides a comprehensive conceptual foundation for future experimental validation and the development of intelligent high-efficiency biogas systems for rural and industrial applications.*

***Keywords:*** Biogas Optimisation, Methane Enhancement, Anaerobic Digestion, Feedstock Pretreatment, Biogas Purification, Renewable Energy Systems.

## I. INTRODUCTION

The increasing demand for sustainable energy and efficient waste management has accelerated the development of renewable energy technologies worldwide. Among these, biogas has emerged as a promising solution for converting organic waste into useful energy through anaerobic digestion. In addition to renewable energy generation, biogas technology helps reduce landfill waste and greenhouse gas emissions, making it suitable for agricultural, rural, and industrial applications focused on decentralised energy production and sustainable waste management.

Biogas is mainly produced from biodegradable materials such as animal manure, food waste, agricultural residues, and sewage sludge. Its primary components are methane ($CH_4$) and carbon dioxide ($CO_2$), along with smaller amounts of hydrogen sulfide ($H_2S$) and moisture. Methane is the main energy-carrying component responsible for combustion and calorific value. However, conventional biogas plants generally produce gas containing only 50–70% methane, while the remaining portion consists mainly of carbon dioxide and impurities that reduce flame quality, thermal efficiency, and practical usability.

Despite the growing use of biogas technology, many conventional biogas plants still operate inefficiently due to poor process optimisation and operational limitations. Common issues include improper feedstock composition, unstable digester temperature, insufficient pretreatment, lack of mixing, and absence of purification systems. These factors negatively affect microbial activity during anaerobic digestion and reduce methane production. Methanogenic bacteria perform efficiently only within mesophilic conditions of approximately: 35 degree Celsius To 38 degree Celsius

Similarly, failure to maintain an optimum carbon-to-nitrogen ratio may result in slower digestion or ammonia inhibition, reducing methane yield. Studies have shown that maintaining a C:N ratio between 25:1 and 30:1 improves microbial activity and methane generation. Mechanical pretreatment methods such as grinding and shredding increase substrate biodegradability, while active bacterial inoculation accelerates digestion and stabilises methane production.

Another major limitation of conventional systems is the lack of effective purification mechanisms. Raw biogas contains carbon dioxide, hydrogen sulfide, and moisture, which reduce fuel quality and cause corrosion and combustion problems. Therefore, purification methods such as water scrubbing, iron oxide filtration, and moisture removal systems are essential for increasing methane concentration and improving biogas quality.

Recent advancements in renewable energy engineering have encouraged the development of smart and integrated biogas systems using automation and process optimisation. However, most existing studies focus only on individual optimisation parameters rather than combining them within a single integrated framework.

Therefore, this study proposes a review-based conceptual model for the design and optimisation of a smart biogas plant aimed at improving biogas production and methane content. The proposed model integrates feedstock optimisation, mechanical pretreatment, thermal management using insulation and solar-assisted heating, sensor-based monitoring, and low-cost purification technologies to improve anaerobic digestion efficiency and biogas quality. The proposed framework provides a sustainable and technically feasible approach for renewable energy generation and efficient organic waste utilisation in rural, agricultural, and small-scale industrial applications.

OBJECTIVES OF THE STUDY –

Methane concentration, digestion efficiency, and overall performance of a typical biogas plant need to be increased and developed accordingly. The following goals can assist in the accomplishment of these areas:

A) Increase methane concentration and total quality in the biogas produced by the plant via integrating optimisation approaches.
B) Create a model of a "smart" biogas plant, including optimised feedstock, thermal conditions, treatment methods, and purification technologies.
C) Evaluate problems with existing biogas facilities, including temperature fluctuations during digestion, improper feed composition, and inadequate or missing treatment methods, as well as deficiencies in purification resources.
D) Investigate how maintaining a proper carbon-to-nitrogen ratio will affect how well anaerobic digestion processes, as well as how much methane will be generated.
E) Determine how different mechanical, thermal, chemical, and biological pretreatment methods improve the biodegradability of substrates and increase the amount of biogas produced.
F) Create a mechanism using insulating materials, underground installations, solar-assisted heating, and sensors to control digestion temperature and maintain mesophilic conditions in the digester.
G) Investigate how improved microbial activity, temperature uniformity, and digestion stability can be achieved through automated process monitoring and controlled mixing systems.
H) Test low-cost methods of purifying biogas to remove carbon dioxide, hydrogen sulphide, and moisture.

## II. LITERATURE REVIEW

Due to its potential for sustainability, biogas technology has become widely accepted as a renewable energy source for local waste disposal, as well as a means of generating electric power. Various researchers have analysed many aspects of biogas production (e.g., anaerobic digestion, feedstock selection, pretreatment procedures, heat treatment, and purification) in an effort to increase overall system performance and to maximise methane output. While there is a wealth of information available on these topics, there are many biogas facilities that still have low performance because of poor process control and the lack of integrated management systems. Studies have demonstrated that the amount of methane produced and the quality of biogas produced are affected by many different factors, including the type of feedstock used, the amount of microbial activity present, ambient temperature stability, and the method of purification.

The emphasis of early investigations was primarily on anaerobic digestion, the biological process. According to Mata-Alvarez et al. (2000), anaerobic digestion involves four stages of biochemistry (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). Gerardi (2003) stated that methane production relies heavily on microbial stability and environmental conditions such as temperature and pH. These two studies have proved the importance of process control in generating biogas.

Feedstock composition has also been identified as a key factor in determining how much methane is produced. According to Yen and Brune (2007), nutrient imbalance and ammonia inhibition due to an improper carbon-to-nitrogen ratio will typically decrease the efficiency of methane production. Studies suggest that a C/N ratio between 25:1 and 30:1 is optimal for methanogenic bacteria. Co-digestion of different substrates has been shown by Li et al (2011) to improve digestion stability and enhance methane production, as well as to provide an adequate level of nutrients.

Research on pretreatment techniques has shown great promise in terms of improving the efficiency of digestion. (2018) Microbial inoculation will aid in the acceleration of digestion startup times and improve the efficiency of methane production. However, the majority of the research to date has focused on the use of a single pretreatment technique rather than on investigating ways of integrating multiple pretreatment techniques for optimal performance.

The regulation of temperature has also been indicated to play a significant role in the efficiency of digestion. Angelidaki and Ahring (1994) demonstrated how the fluctuation of temperature can negatively impact microbial activity and methane production. As a result, several researchers proposed the use of insulation systems, underground digesters, and solar-assisted heating methods to keep mesophilic conditions stable. Additionally, Patil et al. (2020) identified sensor-based monitoring systems as being crucial to maintain stable digestion parameters via automated process control.

In order to increase the concentration of methane and thus improve the quality of biogas, many biogas purification technologies have emerged. In a study by Ryckebosch et al. (2011) found that water scrubbing is a very effective way to remove CO2 from biogas, while Sun et al. (2015) showed that using iron oxide as a filter can effectively remove H2S from biogas and reduce the amount of corrosion this gas will cause. However, most of the adjunct systems used in the purification of biogas are not cost-effective for small-scale operations.

In conclusion, based on prior studies, one can see that the optimisation of the feedstocks used, pretreatment, thermal management, monitoring, and purification technologies will all enhance biogas performance. Nevertheless, little research has been done about how these optimised processes can be integrated into one ‘smart’ biogas facility model. Hence, there is still a requirement for an integrated smart biogas system that is cost-effective and capable of improving the amount of methane produced and the overall efficiency of digestion

**Research Gap Identified**

There has been significant advancement in different areas of biogas optimisations, including: feedstock pre-treatment methods; thermal management; co-digestion methods; automation; and gas purification methods. However, little research has been carried out on the development of a holistic and integrated "smart" biogas plant model that can combine these optimisation strategies into a single coherent and practical system framework. Most of the existing studies have either focused on individual operational parameters in isolation or have been based on costly, large-scale industrial projects, which are not suitable for rural or decentralised applications. Furthermore, there have been very few studies conducted on low-cost smart process control systems which could enhance not only the level of methane concentration in biogas, but also the efficiency of the digestion process as a whole. The current study, therefore seeks to fill this critical void by proposing a conceptual model of a "smart" biogas plant that integrates feedstock optimisation, pre-treatment methods, thermal regulation, controlled mixing, sensor-based monitoring and cost-effective biogas purification methods, together to generate increased methane production, improved quality of biogas, and increased efficiency of conventional biogas plants.

## III. METHODOLOGY

The current study utilises a conceptual review-based research method to explore and analyse the limitations of traditional biogas plants with the goal of creating an optimised smart biogas plant model that will increase methane concentrations and biogas quality. Because the focus of this research is on system design as well as theoretical improvements in performance, there were no experimental or laboratory-scale implementations of the proposed model. The present study is primarily based on available literature, comparative analysis and systems concept development. In order to generate the theoretical basis for this research, the author collected and reviewed any literature generated by other researchers with regard to anaerobic digestion processes, increasing methane yields from biodigesters, feedstock optimisation, means of thermal management of dignified material, purification of biogas, and the application and use of smart monitoring systems. Sources such as various scientific publications, including but not limited to IEEE Xplore, ScienceDirect, Springer, and Google Scholar provided the means by which the author conducted the literature review. The information gathered during the literature review process proved to be valuable with respect to identifying the three primary operational limitations of traditional biogas systems; these limitations include: (1) unbalanced substrates being provided as fodder to the digesters, (2) variable temperature ranges present in anaerobic digesters, (3) insufficient pre-treatment processes, and (4) lack of biogas treatment facilities.

A conceptual smart biogas plant model has been created in order to address the problems identified with existing plants. This new biogas plant will use multiple optimisation techniques fitted together into one operational framework.

The new biogas plant system will perform feedstock optimisation by balancing the carbon-to-nitrogen (C:N) ratio of all feedstocks through controlled methods. Mechanical pre-treatment methods will be used to improve the biodegradability of substrates and the efficiency of digestion. Active bacterial inoculation will be employed during the active digestion process and the use of thermal management (via insulation and solar-assisted heating) will also improve methane production. Automated temperature monitoring and multi-stage biogas purification processes will be implemented on the new biogas plants.

Feedstock optimisation was assessed theoretically using C:N ratio analysis and co-digestion principles to identify organic waste types that could be mixed to produce a stable methane product when used as feedstock. Several mechanical pre-treatment methods (e.g. grinding and shredding) were evaluated in order to ascertain their benefits in improving the conversion rate and efficiency of substrate into methane.

The design of the thermal management system was aimed at ensuring stable mesophilic digestion temperatures using the underground installation of the entire biogas facility, insulation materials, solar hot water, and the use of sensors to monitor temperatures.

The purification component will consist of low-cost gas upgrading technologies (e.g., iron oxide filtration for the removal of hydrogen sulfide and water scrubbing for the reduction of carbon dioxide). Comparisons have been made to show expected improvement in methane concentration (due to the hydrogen sulfide and carbon dioxide removal), digestion stability (through additive use), biogas quality (through multi-stage purification), and overall operational efficiency (based upon the use of alternative energy sources).

## IV. PROBLEMS IN EXISTING BIOGAS PLANTS

The performance, methane output, and overall dependability of traditional biogas facilities are diminished by various technical and operational restrictions. This has an undesirable effect on gut health, biogas quality, and energy produced, especially for smaller and more rural types of biogas plants. Below, we will describe the principal challenges in existing biogas facilities.

*1.* **Improper Feedstock Composition and C: N Ratio Imbalance**

Many conventional biogas plants treat organic waste without maintaining an appropriate ratio of carbon to nitrogen (C:N) for effective anaerobic digestion. Excess carbon will inhibit microbial activity; conversely, excess nitrogen creates ammonia and suppresses methanogenic bacteria, ultimately reducing the overall amount of biogas produced (the methane component).

2. **Lack of Feedstock Pretreatment**

Most existing digesters utilise raw biomass directly as feedstock and do not undergo a pretreatment process. The large particle sizes and complex fibrous structure of the feedstock substrates contribute to the reduced biodegradability. This reduction in substrate biodegradability also slows down the hydrolysis processes and decreases total methanogenesis.

*3.* **Temperature Instability Inside the Digester**

Methanogenic bacteria work most effectively in the mesophilic temperature range (35-38 degrees C). However, most of the existing digesters do not have insulation or heating elements, leading to fluctuations in temperature inside the digester that disrupt the activity of the microorganisms, thereby decreasing the consistency of the overall gas production.

*4.* **Inadequate Mixing and Poor Digester Circulation**

Most conventional biogas plants have little or no mixing system and, in many cases, utilise manual stirring methods for mixing. Poorly mixed substrates result in sediment build-up in the digester, scum formation on the digester surface, and uneven distribution of microorganisms throughout the digester, all of which reduce the efficiency of the microbial digestion process.

5. **Absence of Monitoring and Automated Control Systems**

The vast majority of biogas facilities operate without the constant measurement of critical parameters, like temperature, pH, and gas yield. With no sensor measurement, operators have difficulty maintaining stable operational conditions and discovering problems with engine performance.

*6.* **Low Methane Concentration and Poor Biogas Quality**

Most raw biogas has a methane level of only 50% to 70%. The rest of the gas is largely made up of carbon dioxide, hydrogen sulfide and water vapour, all of which decrease the calorific value, combustion efficiency, and quality of the flame; and all of which cause increased corrosion-related problems.

7. **Lack of Biogas Purification Systems**

Most small-scale biogas facilities do not include technologies for removing carbon dioxide, hydrogen sulfide, or water vapour from the produced biogas. This creates low-quality methane and limits the practicality of using the biogas for end-users.

8. **Lack of Integrated Optimisation Approach**

Most existing biogas facilities are set up to function more efficiently, but each improvement is undertaken separately without regard to integrating feedstock optimisation, thermal management, purification, or smart monitoring into a common operational framework. As a result, overall facility performance and the efficiency of methane production will suffer due to the fragmented approach.

## V. PROPOSED SMART BIOGAS PLANT MODEL

A smart biogas plant integrated anaerobic digestion system, such as this one, will have increased methane concentration, stability of digestion processes, and overall quality of biogas due to optimised processes and intelligent operational control. The above proposed model will include a number of optimisation strategies to overcome the main shortfalls of competing biogas plants that mostly use anaerobic digestion as just a means to produce basic anaerobic digestate.

Four main operational components will be used together with this integrated model

1. Feedstock optimisation
2. Biomass pre-treatments
3. Thermal control/management
4. Biogas purification

When operating together, these processes will increase the growth of the microorganisms involved in anaerobic digestion, reduce the amount of time and energy required to produce methane, and result in a higher-quality biogas that can be used to produce green/sustainable energy.

### 1. Feedstock Optimisation

The most critical aspect influencing the production of methane from the anaerobic digestion of organic wastes is the optimisation of the feedstock supplied to the biogas plant. In traditional biogas plants, organic waste is typically supplied to the digester without accurate nutritional balancing, which results in unstable microbial populations and reduced yields of methane gas. The optimisation of anaerobic digestion requires a C:N ratio that is appropriately maintained because the carbon in organic matter provides energy for microorganisms, while the nitrogen in organic matter supports the growth/metabolism of bacteria.

An incorrect C:N ratio negatively impacts the production of methane from anaerobic digestion. Excess carbon in the feedstock results in slow microbial development because of the nitrogen limitation, whereas excessive nitrogen will cause the formation of ammonia and inhibit the development of methanogenic bacteria. Research has demonstrated that the optimal performance of anaerobic digestion occurs when the C:N ratio of the feedstock supplied to the digester is maintained within the following ranges: 25:1 to 30:1

The composition of organic waste varies in terms of C (Carbon) or GHG emissions as well as N (Nitrogen) content, which is why it's important to include several types of materials together in order to get balanced digestion conditions. An estimated C:N ratio for common carbon-based or GHG-emitting feedstock can be found in Table 1.

Table 1: Approximate C: N Ratio of Common Feedstock Materials

| Feedstock Material | Approximate C:N Ratio | Category |
|---|---|---|
| Cow Dung | 20:1 | Nitrogen-rich |
| Poultry Waste | 10:1 | Highly nitrogen-rich |
| Food Waste | 15-20:1 | Nitrogen-rich |
| Dry Leaves | 50-80:1 | Carbon-rich |
| Straw | 60-100:1 | Carbon-rich |
| Sawdust | 200-500:1 | Highly carbon-rich |

A combination of nitrogen-rich (high nitrogen) substrates with high carbon (carbohydrate) materials is necessary for maintaining an optimised C:N ratio. The primary substrate (cow dung) contains the methanogenic bacteria found in cow dung that will promote completion of anaerobic digestion. Table 2 demonstrates some examples of suitable feedstock combinations.

Table 2: Optimised Feedstock Combinations

| Feed Combination | Estimated C: N Ratio | Expected Result |
|---|---|---|
| Cow dung + food waste | 24-28:1 | Stable methane production |
| Poultry waste + straw | 25-30:1 | Improved digestion efficiency |
| Food waste + dry leaves | 26-30:1 | Balanced microbial activity |

The overall C:N ratio of a feed mixture can be calculated using the weighted average method:

$$C{:}N_{mix} = \frac{(W_1 \times CN_1) + (W_2 \times CN_2) + \ldots}{W_1 + W_2 + \ldots}$$

Where,
$W_1, W_2, \ldots$ = Weight of each feedstock (kg)
$CN_1, CN_2, \ldots$ = C:N ratio of each feedstock
$C{:}N_{mix}$ = Overall C:N ratio of the mixture

For example:

| Feedstock Material | Weight (kg) | C: N Ratio |
|---|---|---|
| Cow dung | 70 | 20:1 |
| Food waste | 20 | 18:1 |
| Dry | 10 | 60:1 |

Calculation:

C:N_{mix}=23.6:1

$$C{:}N_{mix} = \frac{(70 \times 20) + (20 \times 18) + (10 \times 60)}{100}$$

$$= \frac{(1400) + (360) + (600)}{100} \quad \text{(Multiplication)}$$

$$= \frac{2360}{100} \quad \text{(Addition)}$$

$$= 23.6 \quad \text{(Final C:N ratio of mixture)}$$

It is anticipated that improving microbial activity and methane production is accomplished by the calculated value being found within or very near an optimal climatological environmental setting for digestion. Thus, the proper optimization of feedstocks and co-digestion (where two or more feed sources are combined in a single digestion unit) are significant contributors to enhancing both biogas and overall efficiency from an entire biogas production facility.

## 2. Pretreatment of Feedstock

The pretreatment of feedstock is a very significant part of anaerobic digestion because it helps make organic waste more biodegradable, thereby increasing the amount of methane produced from digestion. Many conventional biogas plants feed the raw biomass directly into the digester without processing the feedstock prior to adding it to the digester; this reduces gas production since the microbial activity within the digester takes longer to take effect. The presence of large particles and complicated structures in organic materials such as agricultural waste, kitchen waste, and fibrous biomass makes it challenging for anaerobic bacteria to completely degrade those large organic materials and to access the organic materials for digestion. To assist with these challenges, the proposed smart biogas plant model incorporates both mechanical processing and the use of microorganisms to assist in the anaerobic digestion process and biogas generation.

### *2.1 Mechanical Processing Methods*

Mechanical pretreatment is the physical pre-treatment of organic biomass before digestion, enabling the mechanical methods of grinding, shredding and crushing to reduce the size of large organic material down to a smaller particle size. The mechanical pretreatment will create a smaller particle size, which in turn increases the available surface area for microbial attack, hence making the substrate more accessible for anaerobic digesters and speeding up the hydrolysis process.

The mechanical processes of grinding and shredding will provide a more homogenous slurry, increasing the efficiency of mixing in an anaerobic digester while preventing blockage issues during operation. Anaerobic bacteria are able to decompose small biomass particles more quickly compared to larger biomass particles, producing methane faster than untreated feedstock. Mechanical pretreatment can also be effective for fibrous agricultural by-products, dry leaves, food waste, or crop materials that are normally slow to degrade in a traditional digester.

By increasing the efficiency of anaerobic digestion with mechanical pretreatment, sedimentation is reduced in the reactor and substrate circulation within the reactor is improved. Since mechanical pretreatment uses relatively simple, low-cost equipment and is easy to operate, it is economically advantageous for small biogas applications and rural areas.

### *2.2 Addition of Active Bacteria*

Microbial inoculation is part of the model by adding live active bacteria to help speed up the anaerobic digestion process and increase methane production. Microbial growth in a traditional digester takes months before stable gas production begins; introducing the live active methanogenic bacteria into the first stage of the digestion process increases the stability of the bacteria and reduces startup time.

Cow dung is often used as an inoculum/seed for methane production because it contains anaerobic microorganisms necessary for producing methane. Previously digested slurry or existing bacterial cultures can also be used to help increase microbial activity. The use of these microorganisms speeds up the decomposition of organic material and increases the efficiency of hydrolysis, acidogenesis, and methanogenesis.

The addition of active bacteria will also provide consistent digestion during changes to the feedstock or environmental conditions. Therefore, combining mechanical pretreatment with microbial inoculation helps improve the biodegradability of the substrate, decrease the amount of time required for digestion, stabilise the microbial community, and increase the amount of methane produced overall.

## 3. Thermal Management System

Temperature control is one of the key elements impacting anaerobic digestion as well as the production of methane in biogas plants. Methanogenic bacteria only function efficiently within the mesophilic temperature range of:35 degrees Celsius to 38 degrees Celsius

Many conventional biogas plants suffer from poor thermal management, heat losses and fluctuations of ambient air temperatures, causing poor microbial activity and methane production. The performance of the digestion is detrimental to the efficiency of digestion due to a lack of insulation and unstable temperatures in the digester, and is especially problematic during cooler months.

The proposed smart biogas plant model addresses the issues with poor thermal management and creates a sustainable approach to biogas production through the use of insulation systems, underground installations, solar-assisted heating and monitoring temperatures to ensure stable conditions for digestion and increased overall efficiency of biogas production.

### *3.1 Underground Digester Installation*

This currently proposed model includes either partly or totally burying the digester in order to reduce heat loss and maintain a more consistent temperature inside the digester. The soil around the digester will serve as a natural thermal barrier, reducing rapid fluctuations in temperature due to outside weather.

Additionally, placing the digester underground will shield it from wind and sunlight, both of which will lead to a more stable and consistent internal environment conducive to microbial activity.

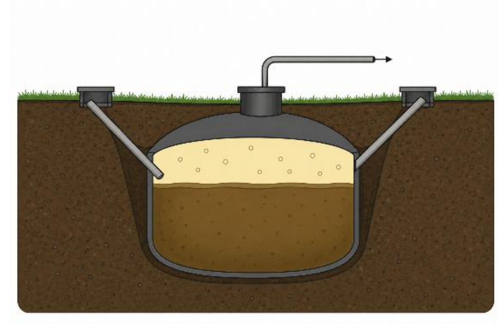

Fig 1: Underground Digester

While both underground and above-ground digesters are capable of maintaining thermal stability, an underground digester will generally require less energy to heat since it has a reduced amount of heat loss due to natural thermal barriers. The method of regulating the temperature of the digester through the use of natural thermal barriers is cost-effective since it reduces heating requirements for the digester and creates more consistent digestion without the use of additional energy.

### *3.2 Insulation Layer Around the Digester*

In order to decrease thermal losses, the proposed model would utilise an insulation layer along the perimeter of the digester walls to retain heat produced during anaerobic digestion (AD) and prevent heat loss from the anaerobic digester to the environment. This allows for more consistent microbial activity and reduces temperature fluctuations inside the digester.

Fibreglass wool and polyurethane foam are two types of insulation material that are used in the proposed system because of their low thermal conductivities and ability to retain heat. Fibreglass wool, due to its light weight, cost-effectiveness, and high resistance to heat transfer, can be used to keep a stable temperature in the anaerobic digester. Polyurethane foam would provide thermal insulation and be resistant to moisture, further aiding in long-term operational stability.

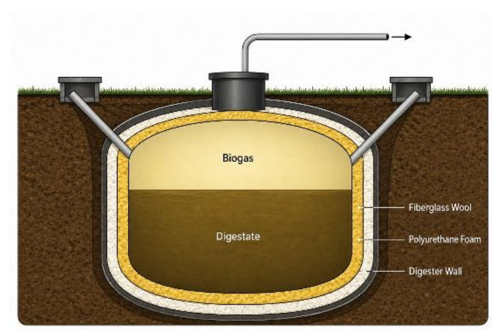


Fig 2: Insulation layer around digester

These insulation materials were chosen because they are readily available, economically reasonable, and capable of significantly reducing the loss of heat from biogas systems. The insulation layer will also reduce the amount of energy needed to operate auxiliary heating systems, resulting in more efficient anaerobic digestion.

### *3.3 Solar Water Heater Coil-Based Heating System*

One significant feature of this smart biogas facility design is its use of solar power to support maintaining optimum digestion temperatures. Many of today's fabric-covered digesters rely on electric or gas combustion to run their external heating devices, which causes a rise in operation cost through electrical or fuel use. This system's disadvantages are eliminated in the solar heat-assisted system and the use of renewable solar energy for thermal regulation. Solar power from the sun is converted into hot water using a solar water heater connected via a coil loop to be able to flow through metallic coils located around the inner walls of the digester chamber and/or inside the slurry chamber. During daylight hours, solar collectors heat the water and store it in an insulated storage tank. The hot water is pumped throughout the metalliferous coils, and as the hot water passes over the coils' surfaces, to raise the temperature inside the digester to create ideal living conditions for the Methanosarcina sp. methanogenic bacteria.

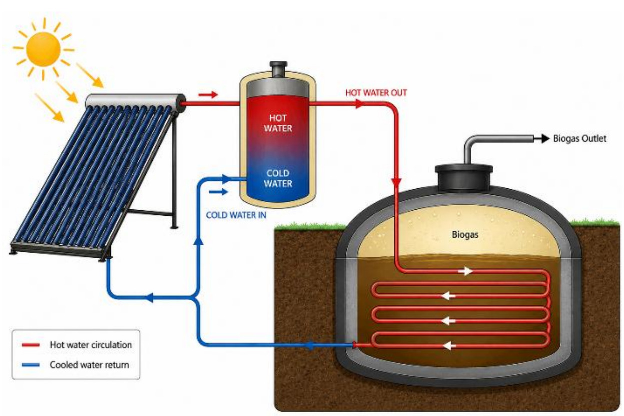


Fig 3: Solar Heater coil-based heating system

With this design, the temperature of digestion will become very stable through cold days and help prevent the temperature from dropping at an abrupt pace, which negatively impacts the activity of the microorganisms. In addition to having fewer CO2 emissions than the traditional electrically heated digesters, the solar heating system will reduce the operation energy consumption and improve the economic viability of the biogas facility for rural and decentralised communities.

### *3.4 Temperature Monitoring and Automated Control System*

The proposed smart biogas plant will feature an automated control and temperature monitoring system that can provide consistent conditions for digestion. Conventional biogas plants typically do not have the ability to monitor temperature in real-time, leading to heat loss, inconsistent microbial activity, and lower methane production.

The proposed system will continuously monitor the internal temperature of the digester using temperature sensors that are installed inside the digester. The sensor data will be sent to a control unit, which will automatically control the solar heating system. When the temperature in the digester falls below the

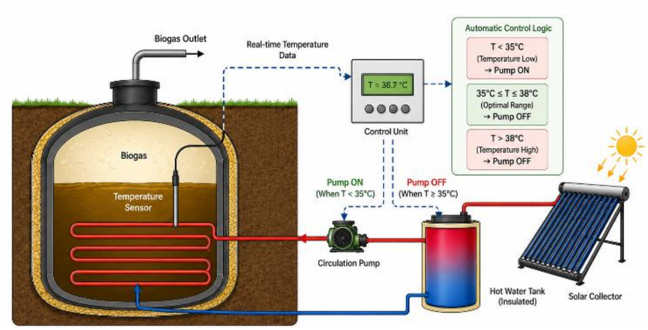


Fig 4 : Temperature monitoring and automated control system

optimum mesophilic temperature range, the control system will turn on the hot water circulation pump; when the temperature in the digester reaches the desired temperature, the control system will automatically turn off the hot water circulation pump to prevent overheating and energy loss.

In addition to improving digestion stability and reducing the manual effort to maintain favourable conditions for methanogenic bacteria, this automated system will also improve the thermal performance of the biogas plant compared to conventional biogas plants by reducing the thermal losses of the plant and increasing the efficiency of methane generation. In addition, a combination of the plant's underground installation, insulation layers, solar-assisted heating, and automated temperature control will improve the stability and increase the efficiency of the methane production compared to conventional biogas plants.

## 4. Biogas Purification System

Conventional digesters produce raw biogas that contains several impurities, including carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), moisture and methane ($CH_4$). These impurities can lower the calorific value of the biogas, reduce combustion efficiency, and cause problems including corrosion, odour and condensation in pipelines and burners. The proposed smart biogas plant is designed to include a low-cost multi-stage system to purify the raw biogas to increase the concentration of methane and the overall quality of the biogas.

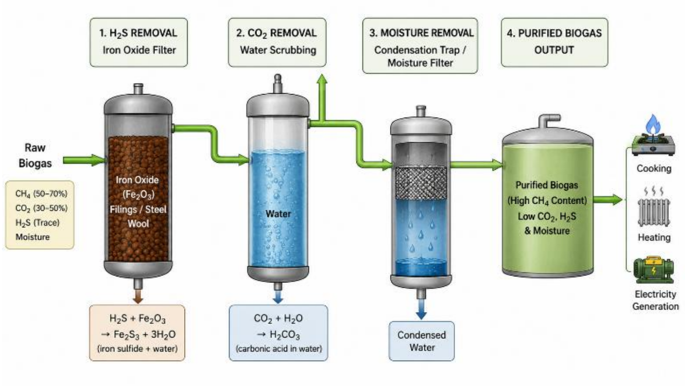


Fig 5: Biogas Purification System

### *4.1 Hydrogen Sulfide ($H_2S$) Removal*

Pipelines, burners, and storage systems are all susceptible to serious damage from hydrogen sulfide because it is extremely corrosive and toxic. An iron oxide filtration chamber that is filled with either iron filings or steel wool will be used in this case; once the biogas passes through the chamber, the H2S will react with iron oxide to form iron sulfide as per the formula below:

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O$$

This process reduces corrosion, odour, and equipment damage while remaining economical for rural and small-scale applications.

### *4.2 Carbon Dioxide ($CO_2$) Removal Using Water Scrubbing*

Carbon dioxide creates a decrease in methane level and combustion in biogas. This system of removal uses a water scrubber as an interface for contacting raw biogas. This treatment process occurs by having raw biogas pass into a water chamber where $CO_2$ is more soluble than methane; therefore, as $CO_2$ dissolves into the water, methane will leave the top of the chamber through the outlet. This chemical reaction can be represented by the following equation:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

If successful, this method will increase methane concentration, increase the calorific value, and increase the efficiency of combustion while not requiring any expensive chemicals or complicated equipment.

### *4.3 Moisture Removal*

Water vapor in raw biogas may lead to corrosion, condensation, and unreliable combustion as well as require removal by both moisture filters and condensation traps installed after the scrubbing unit. Other moisture-removing methods could involve silicate gel materials used to help reduce the volume of water vapour in an efficient manner.

### *4.4 Purified Biogas Output*

The final purified gas has less impurities than the raw biogas and more methane. The quality of flame produced from burning the purified biogas is better than that produced from burning raw biogas because of its higher energy content, less corrosive nature, and higher combustion efficiency. Therefore, purified biogas can be used for all applications that require heat, such as cooking, heating, and generating electricity.

## VI. EXPECTED PERFORMANCE IMPROVEMENT

The new proposed smart biogas plant model is expected to lead to increased methane output, improved consistency in digestion acceptance, improved quality of biogas, and overall increased operational efficiency than conventional biogas plants. Currently, conventional biogas facilities do not adequately manage feedstock, leading to unacceptable variances in temperature, less production of methane, and little if no purification, ultimately creating low-efficiency electricity generation. The proposed smart biogas plant model addresses feedstock issues through optimising feedstock, mechanically processing feedstock (pretreatment), thermally controlling the biogas process (heating), automatic monitoring of the production process, and purifying biogas.

Optimising the carbon-to-nitrogen (C:N) ratio of the feedstock will allow for increased microbial activity through anaerobic digestion. Mechanical pretreatment, which consists of grinding and shredding, will enhance the biodegradability of the substrate, leading to increased rates of methane production. Thermally controlling the temperature of the anaerobic biogas digestion process through below-ground installation, insulation, solar heating, and temperature monitoring will allow for maintained mesophilic temperatures (35–38°C), leading to increased rates of methane production.

Removing hydrogen sulfide, carbon dioxide, and moisture using iron oxide filters and water scrubbers during biogas purification will positively impact the improvement of the biogas quality by increasing the methane concentration from approximately 50–70% in conventional systems to approximately 80–95% in the proposed system. The use of automatic control systems and sensor-based monitoring to determine the operational variables of the biogas production process will provide for increased stability in both the processor and reduce manual intervention. Thus, the proposed smart biogas plant will provide an increase in the energy conversion efficiency of produced electricity and develop cleaner biogas products.

## VII. ADVANTAGES

Compared to their traditional counterparts, the new smart biogas plant design provides many benefits related to its operational processes, technical functions and environmental impact. Feedstock optimisation, thermal regulation, smart monitoring systems and purification systems increase the efficiency and reliability of anaerobic digestion.

***1. Increasing production of methane:***

By having the correct composition of feedstock and having stable conditions for digestion, it has been proven that there is higher activity of the micro-organisms and therefore results in higher levels of methane in the biogas produced.

***2. Improving the quality of biogas:***

The biogas purification system is able to remove carbon dioxide, hydrogen sulphide and moisture from the biogas to produce a higher quality, cleaner, higher calorific value and more efficient burning biogas.

***3. Consistent performance of the digester:***

By effectively managing the thermal energy in the digester, it is possible to keep the temperature within the mesophilic temperature range, which results in stable microorganisms in the digester and consistent levels of gas production.

***4. Reducing operational losses:***

The installation of insulation layers and underground digesters means that there is less loss of heat from the digesters, which results in better energy efficiency.

***5. Renewable Energy Utilisation:***

The solar heating system reduces dependence on conventional electrical heating and promotes sustainable energy usage.

***6. Smart Monitoring and Automation:***

Temperature sensors and automated controls enable real-time monitoring and improve operational reliability.

***7. Improved Waste Management:***

The system efficiently converts organic waste into biogas and nutrient-rich slurry for agricultural use.

***8. Reduced Maintenance Problems:***

Removal of hydrogen sulfide and moisture reduces corrosion, blockage, and equipment damage.

***9. Environmental Sustainability:***

The proposed system reduces greenhouse gas emissions and supports sustainable waste-to-energy conversion.

***10. Scalability:***

The modular design allows implementation in domestic, agricultural, and small-scale industrial applications.

## VIII. LIMITATIONS

Despite its advantages, the proposed smart biogas plant model also has certain technical and practical limitations.

***a) High Initial Installation Cost:***

The addition of solar heating systems, sensors, insulation materials, and purification units increases the overall setup cost of the plant.

***b) Dependence on Monitoring Systems:***

Failure of sensors or automated control units may disturb temperature regulation and digestion stability.

***c) Need for Technical Expertise:***

Installation, operation, and maintenance of smart systems require proper technical knowledge and skilled personnel.

***d) Maintenance Complexity:***

Purification units, sensors, and filtration materials require regular maintenance and periodic replacement.

***e) Power Dependency:***

Automated monitoring systems and circulation pumps require a continuous electricity supply or backup power systems.

***f) Sensor Calibration Issues:***

Incorrect sensor readings may lead to improper temperature control and unstable digester operation.

***g) Adoption Challenges in Rural Areas:***

Limited technical awareness and financial limitations may reduce adoption in rural and economically weaker regions.

***h) Scalability Constraints:***

Feedstock availability, climate conditions, and land requirements may limit large-scale implementation in some areas.

## IX. CONCLUSION

This research evaluated the predominant technical and operational deficiencies that can be found in conventional biogas facilities and proposed a new integrated 'Smart Biogas Facility' model to increase methane concentrations, digestion stability, and the quality of biogas. Conventional biogas facilities experience problems like inadequate feedstock management, unstable digestate temperatures, under- or non-treated feedstock, and insufficient rate of purification, which all contribute to low levels of biogas production and inefficient energy utilisation. While anaerobic digestion technology has large potential as a sustainable form of renewable energy generation and waste management, these factors decrease the overall effectiveness of anaerobic digesters.

The Smart Biogas Facility model combines complete integration of feedstock optimisation, mechanical pre-treatment, thermo-control, automated monitoring, and multi-stage biogas purification into one facility, which is operated in an effective manner. For example, by using controlled C:N ratios, it is possible to balance the feedstock to improve the activity of the microbes and create efficiency in digestion; mechanical pre-treatment and actively seeding the microbial population enhance the biodegradability of the feedstock and the production of methane. The thermo-control component of the facility consists of an underground installation with insulation, solar heating, and temperature monitoring that will ensure mesophilic conversion temperatures (35–38°C) so that microbial growth will be stable and the facility will produce gas at a continuous rate.

The goal of this system is to produce high-quality biogas by removing impurities (e.g., hydrogen sulphide and carbon dioxide) from the biogas and preventing any further build-up of moisture. The way that this will occur is through using iron oxide filtration and water scrubbing techniques to remove the aforementioned impurities. As a result, the new model will be able to produce higher methane concentrations with greater combustion efficiency and overall operation reliability compared to traditional methods. Additionally, the use of smart monitoring systems, combined with renewable energy-based (solar or wind-powered) heating sources and cost-effective methods of filtering impure gases from biogas, helps contribute to reducing the amount of greenhouse gases released into the atmosphere using more environmentally sound means, as well as provide improved ways of utilising waste while efficiently producing energy.

In conclusion, the proposed smart biogas plant model provides a viable technological solution to producing efficient energy from waste and serves as a basis or starting point for developing future smart, high-efficiency biogas plants capable of producing energy from waste at rural or agricultural communities, and local industrial facilities on a small scale.

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