

EFFECTS OF HYDRAULIC RETENTION TIME AND PH FOR THERMAL EFFICIENCY IN BIOGAS PRODUCTS FROM FOOD WASTE VIA ANAEROBIC DIGESTION METHOD

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Abstract

This study explores the influence of hydraulic retention time (HRT) and pH on the efficiency of biogas production and methane (CH₄) concentration in anaerobic digestion systems. Findings indicate that extending HRT enhances biogas output and improves methane purity, while simultaneously reducing levels of carbon dioxide (CO₂), oxygen (O₂), and nitrogen (N₂), reflecting more effective methanogenic activity. As HRT increases from 10 to 30 days, biogas yield improves from 0.6 to 1.0 m³/kg.VS, and CH₄ concentration rises from 54.71% to 65.92%. The decline in CO₂ content from 37.89% to 31.38% further supports the development of more stable anaerobic conditions. Despite these benefits, extended HRTs require larger digester capacities and raise operational expenses, underlining the necessity of identifying an economically viable operational window. At an HRT of 30 days, pH variation shows that methane levels grow from 63.78% at pH 6.0 to a peak of 73.46% at pH 9.0, with optimal methanogenesis observed between pH 7.0 and 8.5. The study also observes significant reductions in chemical oxygen demand (COD) within the first 10 days, indicating rapid breakdown of organic substrates. Alkaline conditions appear to mitigate the inhibitory effects of volatile fatty acids, thereby enhancing methane quality, calorific value, and thermal efficiency. Overall, the result showed that emphasize the critical role of fine-tuning both HRT and pH to maximize biogas yield, improve energy recovery, and promote more sustainable anaerobic digestion system performance.

Keyword: Biogas, Thermal efficiency, Food waste, Anaerobic Digestion

1. Introduction

The increasing reliance on fossil fuels and the escalating effects of climate change have driven a global shift toward sustainable energy alternatives. Among these, biogas production via anaerobic digestion (AD) has garnered significant attention as a renewable energy technology. Anaerobic digestion involves the microbial breakdown of organic materials in the absence of oxygen, resulting in the production of biogas, which is primarily composed of methane (CH₄) and carbon dioxide (CO₂) [1]. Food waste, which is rich in biodegradable organic content, is considered a highly suitable feedstock for AD due to its abundance and potential to address both energy production and waste management challenges simultaneously [2], [3]. Despite its promise, optimizing methane

production and ensuring thermal efficiency in AD systems remain critical for maximizing the viability of this technology. Methane yield, a key indicator of AD performance, is influenced by substrate characteristics, microbial community dynamics, and operational parameters [4]. For instance, the carbon-to-nitrogen (C/N) ratio is a critical factor in maintaining microbial activity and process stability. Imbalanced C/N ratios can lead to ammonia inhibition or nutrient limitations, both of which can compromise methane production [5]. Additionally, the presence of inhibitory substances, such as heavy metals or volatile fatty acids, can disrupt microbial metabolism, necessitating proper feedstock selection and preparation [6].

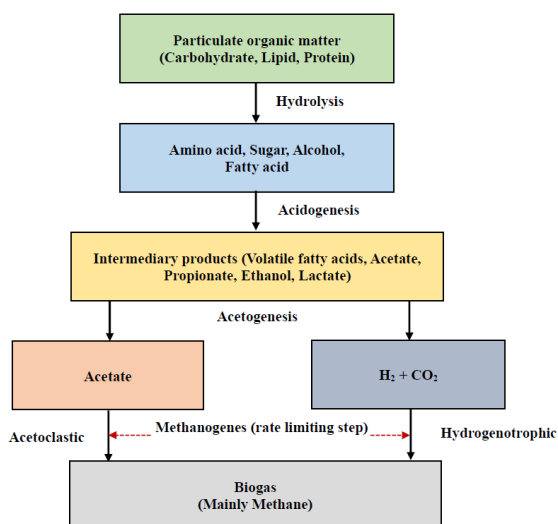


Figure 1. Biogas production process [17-20]

Pre-treatment technologies have been widely studied to enhance the biodegradability of organic materials and improve methane yields. Methods such as thermal treatment, chemical addition, mechanical disintegration, and enzymatic hydrolysis have been shown to break down complex organic polymers into simpler, more accessible compounds for microbial digestion [7], [8]. These approaches not only enhance substrate bioavailability but also accelerate the hydrolysis stage, which is often a rate-limiting step in AD. Operational parameters such as temperature, pH, and hydraulic retention time (HRT) also play pivotal roles in determining methane yields. Mesophilic (30–40°C) and thermophilic (50–60°C) temperature ranges support distinct microbial communities, each with specific metabolic capacities and stability characteristics [9]. Maintaining optimal pH levels between 6.8 and 7.2 is essential for methanogenic activity, while appropriate HRT ensures sufficient time for the complete digestion of organic materials [10].

Thermal efficiency, another crucial aspect of biogas systems, involves maximizing the energy recovery and utilization from both biogas and digestate. The use of heat recovery systems, such as combined heat and power (CHP) units, [21-23] can significantly improve the energy balance of AD facilities by capturing waste heat for internal process use or external applications [11]. Co-digestion, where food waste is processed alongside other organic materials such as livestock manure or agricultural residues, has emerged as a practical approach to improve system efficiency. This strategy not only provides a more balanced nutrient profile for microorganisms but also enhances methane yields through synergistic effects between different substrates [12], [13].

The integration of advanced technologies and a deeper understanding of these influencing factors have the potential to overcome existing limitations in AD systems. By optimizing methane enhancement and thermal efficiency, biogas production can be transformed into a more reliable and scalable energy solution. [24-28] This paper aims to explore the critical factors affecting methane yield and thermal efficiency in AD processes, with a focus on recent advancements in technology and best practices for food waste utilization. [29-32] Fig.1. illustrates the biological breakdown of organic waste through a four-stage process known as anaerobic digestion, which ultimately converts complex organic matter into methane rich biogas. This sustainable biochemical pathway relies on a sequence of distinct microbial groups. The process begins with Hydrolysis, the initial stage where complex particulate organic matter consisting of macromolecules like carbohydrates, lipids, and proteins is broken down by extracellular enzymes. This step liquefies and dissolves the large polymers into smaller, soluble monomers, specifically amino acids, sugars, alcohols, and fatty acids. Once these soluble compounds are formed, they enter the second stage, Acidogenesis. During this fermentative phase, acid-forming bacteria metabolize the monomers to produce a variety of intermediary products. These intermediaries primarily consist of volatile fatty acids (VFAs), along with acetate, propionate, ethanol, and lactate. In the third stage, Acetogenesis, these intermediary products are further digested by acetogenic bacteria. This step is crucial as it refines the volatile fatty acids into compounds that can be directly utilized by the final group of microorganisms. The acetogenesis stage splits the metabolic pathway into two primary precursors: acetate on one side, and a mixture of hydrogen gas and carbon dioxide) on the other. The final and most critical phase of the flowchart is Methanogenesis, which is explicitly highlighted as the rate-limiting step of the entire anaerobic digestion process. During this stage, strictly anaerobic archaea called methanogens convert the preceding biochemical products into the final output. This occurs via two distinct microbial pathways: the Acetolactic pathway, which utilizes the acetate, and the Hydrogenotrophic pathway, which utilizes the mixture. The culmination of these synchronized pathways results in the generation of biogas, a renewable energy source composed mainly of methane.

Table 1. Composition of biogas.

Component	Typical Composition (%)	Description	Ref.
Methane (CH ₄)	50–75%	Primary energy carrier: flammable and odorless	[14,15]
Carbon Dioxide (CO ₂)	25–50%	Non-flammable gas: reduces the calorific value of biogas	[14,16]
Water Vapor (H ₂ O)	0–10%	Present due to the wet digestion process	[15,16]
Hydrogen Sulfide (H ₂ S)	0.1–3%	Toxic and corrosive: needs removal for energy applications	[14,16]
Nitrogen (N ₂)	0–5%	Non-reactive and inert: may dilute the gas	[14,15]
Oxygen (O ₂)	0–1%	Trace amounts: can affect combustion efficiency	[16]
Hydrogen (H ₂)	0–1%	Adds minimal energy value but rarely present in high amounts	[15]
Ammonia (NH ₃)	Trace	Typically negligible but may contribute to odor	[14,16]

For Table 1. outlines the typical chemical composition of biogas, detailing the primary gases, secondary impurities, and trace elements that form this renewable energy source. Understanding these components is essential, as the practical utility and heating value of biogas depend heavily on the balance between its energy-yielding gases and its problematic impurities. The foundational value of biogas lies in its highest concentration component, Methane (CH_4), which makes up 50–75% of the total mixture. As a flammable and odorless gas, methane serves as the primary energy carrier of biogas. Conversely, the second largest component is Carbon Dioxide (CO_2), accounting for 25–50% of the volume. Unlike methane, carbon dioxide is non-flammable and acts as a diluent that reduces the overall calorific (heating) value of the gas.

Beyond these two main bulk gases, biogas contains secondary components and impurities introduced during the biological breakdown process. Water Vapor (H_2O) is found at levels of 0–10%, which naturally occurs due to the wet nature of the anaerobic digestion process. A more critical impurity is Hydrogen Sulfide (H_2S), which ranges from 0.1–3%. Despite its relatively small percentage, H_2S is highly toxic and corrosive, requiring strict removal before the biogas can be safely used in energy applications. Nitrogen (N_2) is also present at 0–5% as a non-reactive, inert gas that can further dilute the gas mixture. Finally, the table lists several elements that appear only in minor or trace quantities. Both Oxygen (O_2) and Hydrogen (H_2) are typically restricted to 0–1% of the total composition; oxygen can negatively affect combustion efficiency, while hydrogen contributes a minimal energy value but rarely accumulates in high amounts. Lastly, Ammonia (NH_3) exists in mere trace levels; while its volume is typically negligible, it is noted for its potential contribution to the overall odor of the biogas. For objective of research is investigate the effects of hydraulic retention time (HRT) on biogas production, biogas composition, and chemical oxygen demand (COD) removal efficiency during the anaerobic digestion of food waste., Evaluate the effects of pH on biogas quality, particularly methane (CH_4) concentration, heating value, and thermal efficiency in the biogas production process. And determine the optimal operating conditions of HRT and pH for maximizing biogas production, methane quality, COD removal efficiency, and energy recovery from food waste through anaerobic digestion. This study differs from previous research by simultaneously evaluating the effects of hydraulic retention time (HRT) and pH on biogas production, methane concentration, COD removal, heating value, and thermal efficiency using food waste as the sole substrate. The results showed that increasing HRT from 10 to 30 days enhanced biogas yield from 0.6 to 1.0 m^3/kg VS and increased methane concentration from 54.71% to 65.92%, while achieving COD removal efficiencies of 72.0–73.6%. Furthermore, increasing pH from 6.0 to 9.0 improved methane concentration to 73.46%, resulting in a higher heating value (1,780.25 kJ/kg) and maximum thermal efficiency (64.35%). Unlike many previous studies that focus primarily on methane yield, this research integrates waste treatment performance, biogas quality, and energy efficiency into a single evaluation framework. These findings provide a comprehensive approach for optimizing anaerobic digestion systems and maximizing renewable energy recovery from food waste.

2. Experimental setup

2.1 Biogas digester using anaerobic system

A biogas digester using the anaerobic method is a system that converts organic waste into biogas through microbial activity in the absence of oxygen. The process consists of four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex organic compounds such as carbohydrates, proteins, and fats break down into simpler molecules. Acidogenesis further converts these molecules into volatile fatty acids, hydrogen (H_2), and carbon dioxide (CO_2). Acetogenesis transforms these acids into acetic acid, CO_2 , and H_2 . Finally, methanogenesis occurs, where methanogenic archaea convert acetic acid and hydrogen into methane (CH_4) and CO_2 , the primary components of biogas. The result showed that biogas can be used as an energy source for cooking, heating, and electricity generation. The efficiency of the process depends on temperature, pH, carbon-to-nitrogen ratio (C/N), and organic loading rate. This sustainable technology reduces greenhouse gas emissions and provides a renewable energy source while managing organic waste effectively.

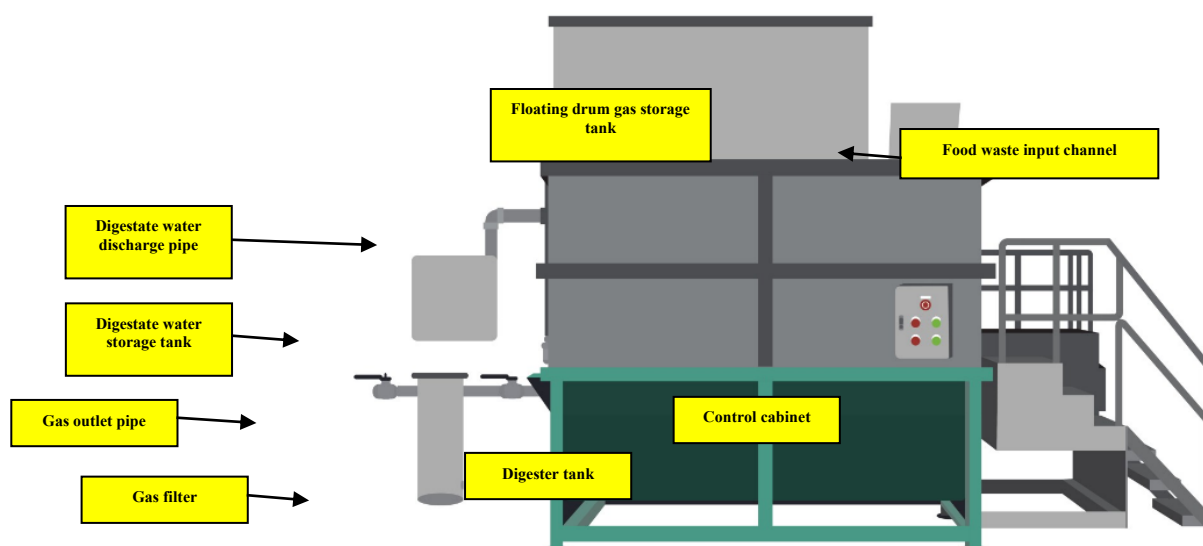


Figure 2. Biogas Digester using Anaerobic method

For figure 2 is the biogas digester operates based on the anaerobic digestion process, which involves the breakdown of organic matter such as food waste by microorganisms in the absence of oxygen. The key steps are as follows: Food Waste Input: Organic waste is introduced through the food waste input channel into the digester tank. This tank provides an oxygen-free environment essential for anaerobic microorganisms to thrive. Anaerobic Digestion: Inside the digester tank, microorganisms decompose the organic material. This process occurs in several stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. As a result, biogas mainly composed of methane (CH_4) and carbon dioxide (CO_2) is produced. Biogas Collection: The produced gas rises and is collected in the floating drum gas storage tank, which moves up and down depending on the amount of gas stored. Gas Outlet and Filtering: The biogas flows out through the gas outlet pipe and passes through a gas filter to remove impurities like hydrogen

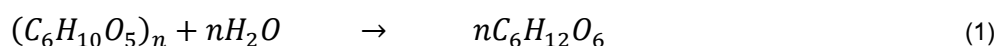
sulfide, making it cleaner and safer for use as an energy source. Digestate Management: The remaining slurry, called digestate, contains nutrients and can be used as a bio-fertilizer. The digestate water flows into the digestate water storage tank through the digestate water discharge pipe for further handling or use. System Control: The control cabinet manages the operation of the digester system, ensuring optimal temperature, pressure, and mixing conditions for efficient biogas production.

2.2 Anaerobic Digestion Process [33-41]

The production of biogas occurs in four main stages:

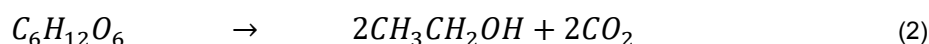
Hydrolysis

The carbohydrates, proteins, and fats in organic materials (e.g., animal manure, and food waste) are broken down by enzymes produced by microorganisms into simpler molecules. Example reaction:



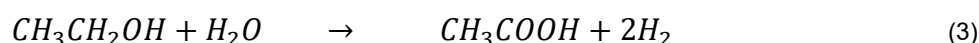
Acidogenesis (Formation of organic acids)

Acidogenic bacteria convert the organic compounds produced during hydrolysis into volatile fatty acids (VFAs), alcohols, hydrogen (H_2), and carbon dioxide (CO_2). Example reaction:



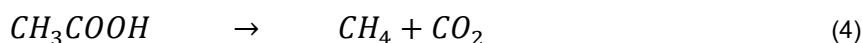
Acetogenesis (Conversion into Acetate)

Volatile fatty acids (VFAs) and alcohols are further broken down into acetic acid (CH_3COOH), hydrogen (H_2), and carbon dioxide (CO_2). Example reaction:

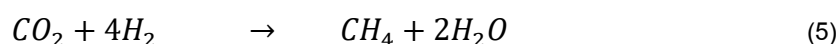


Methanogenesis (Production of methane)

Methanogenic archaea convert acetic acid (CH_3COOH), hydrogen (H_2), and carbon dioxide (CO_2) into methane (CH_4). Example reactions:



Acetic acid is converted into methane and carbon dioxide. Or



Hydrogen and carbon dioxide are converted into methane and water.

2.3 Preparation experimental

As the hydraulic retention time (HRT) increases from 10 to 30 days, biogas production efficiency improves significantly. At HRT 10 days, microbial activity is limited, leading to lower methane yield and reduced biogas quality. Extending HRT to 20 days enhances the digestion process, allowing methanogenic bacteria to convert more organic matter into methane, resulting in higher biogas volume and energy content. At HRT 30 days, the system reaches optimal conditions, maximizing methane production and thermal efficiency. Longer retention times provide sufficient time for complete anaerobic digestion, improving overall biogas yield and quality. However, excessively long HRTs may reduce system efficiency due to substrate depletion and operational constraints. Therefore, balancing HRT is essential for optimizing biogas production performance.

2.4 Thermal efficiency of biogas [42-47]

The thermal efficiency of biogas from food waste depends on multiple factors, including the composition of the biogas, the efficiency of the combustion system, and the type of engine or burner used. Here are some key points:

1. Biogas Composition

- Biogas from food waste typically consists of 50–70% methane (CH_4), 30–50% carbon dioxide (CO_2), and small amounts of other gases (e.g., H_2S , H_2O).
- The higher the methane content, the higher the energy value of the biogas.

2. Energy Content

- The energy content of pure methane is $\approx 55.5 \text{ MJ/kg}$ or $\approx 39.8 \text{ MJ/m}^3$.
- Biogas with 60% methane typically has an energy value of $\approx 22\text{--}24 \text{ MJ/m}^3$.

3. Thermal Efficiency in Different Systems

- Biogas burners (direct heat applications): 55–85% efficiency
- Gas engines (electricity generation): 30–40% efficiency
- Combined heat and power (CHP) systems: 60–90% efficiency (total heat + electricity output)
- Fuel cells: Can reach 50–60% efficiency

The thermal efficiency of gas derived from food waste is an important parameter to evaluate its potential as an alternative energy source. It is determined by the amount of energy released during combustion relative to the energy input. The key parameters influencing thermal efficiency include the calorific value of the gas, combustion efficiency, and heat transfer efficiency in the utilization system.

The thermal efficiency (η) of the system can be expressed as:

$$\eta = \frac{Q_{\text{useful}}}{Q_{\text{input}}} \times 100 \quad (6)$$

Where:

Q_{useful} is useful heat energy output (Joules or kcal)

Q_{input} is total energy input from the gas (Joules or kcal)

For biogas combustion, the thermal efficiency of a burner or engine can also be estimated using:

$$\eta = \frac{mC_p\Delta T}{LHV \times m_{\text{fuel}}} \times 100 \quad (7)$$

Where:

M is mass flow rate of the working fluid (kg/s)

C_p is specific heat capacity of the fluid (J/kg·K)

ΔT is temperature change of the fluid (K)

LHV is calorific value of the gas (J/kg or J/m³)

m_{fuel} is mass flow rate of the fuel (kg/s)

In practice, thermal losses occur due to incomplete combustion, heat dissipation, and system inefficiencies. Enhancing gas purity (reducing CO₂ and moisture content) and optimizing combustion conditions can improve efficiency. This study investigated the effects of hydraulic retention time (HRT) and pH on biogas production, methane concentration, and thermal efficiency using a food-waste anaerobic digestion system. Food waste was used as the substrate and fed into a laboratory-scale anaerobic biogas digester operating under oxygen-free conditions. The anaerobic digestion process involved four biological stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, during which organic matter was converted into biogas consisting mainly of methane (CH₄) and carbon dioxide (CO₂). To evaluate the effect of retention time, the digester was operated at HRTs of 10, 20, and 30 days. Biogas production, gas composition (CH₄, CO₂, O₂, and N₂), and chemical oxygen demand (COD) were measured to assess digestion performance and organic matter degradation. The influence of pH on biogas quality was also investigated by adjusting the digestion conditions and monitoring changes in methane concentration and energy content. The thermal performance of the produced biogas was evaluated using calorific value and thermal efficiency calculations. Thermal efficiency was determined from the ratio of useful heat output to total energy input, considering the methane content and heating value of the biogas. The relationships among HRT, pH, methane production, COD removal, and thermal efficiency were analyzed to identify the optimal operating conditions for maximizing biogas yield, improving gas quality, and enhancing energy recovery from food waste.

3. Results and discussion

3.1 Effect of hydraulic retention time (HRT) on biogas production

The study investigates the effect of hydraulic retention time (HRT) on biogas production and its composition. HRT is a crucial parameter in anaerobic digestion, representing the average time that organic material remains in the digester before being converted into biogas. The efficiency of biogas production is highly dependent on the duration of HRT, as it directly affects the breakdown of volatile solids (VS) and the activity of methanogenic bacteria responsible for methane (CH₄) generation. According to the experimental data presented, an increase in HRT leads to a significant improvement in both the volume of biogas produced and its methane content. At an HRT of 10 days, the biogas yield is 0.6 m³/kg.VS, with a methane concentration of 54.71%. When the retention time is extended to 20 days, the biogas yield increases to 0.8 m³/kg.VS, and the methane concentration rises to 60.95%. At 30 days HRT, the biogas yield reaches its peak at 1.0 m³/kg.VS, with the highest methane content of 65.92%. This trend clearly indicates that a longer retention time enhances the anaerobic digestion process, allowing more complete degradation of organic matter and an improved conversion rate into methane. Furthermore, the

concentration of carbon dioxide (CO_2) in the biogas gradually decreases as the HRT increases. At 10 days, the CO_2 concentration is 37.89%, which drops to 35.89% at 20 days and further reduces to 31.38% at 30 days. This decline in CO_2 suggests a higher efficiency of methanogenesis, where organic acids and intermediates are more effectively converted into methane rather than accumulating as carbon dioxide. This improvement in methane-to-carbon dioxide ratio results in a higher-quality biogas with better combustion characteristics.

Table 2. Effect of hydraulic retention time (HRT) on biogas production

Hydraulic retention time (day)	Biogas volume ($\text{m}^3/\text{kg.VS}$)	%Volume concentration			
		% CH_4	% CO_2	% O_2	% N_2
10	0.6	54.71	37.89	0.97	6.43
20	0.8	60.95	35.89	0.94	2.22
30	1.0	65.92	31.38	0.85	1.85

Another important observation from the data is the reduction in oxygen (O_2) and nitrogen (N_2) concentrations with increasing HRT. At 10 days, oxygen concentration is 0.97%, and nitrogen is 6.43%. These values drop to 0.94% and 2.22% at 20 days, respectively, and further decline to 0.85% and 1.85% at 30 days. The decreasing levels of oxygen and nitrogen indicate a more controlled anaerobic environment, minimizing external air intrusion into the digester. This is critical for maintaining an optimal anaerobic condition, as excessive oxygen presence can inhibit methanogenic activity and lead to inefficient biogas production. The result showed that confirm that increasing HRT enhances biogas yield and methane concentration while reducing undesirable gases such as CO_2 , O_2 , and N_2 . The reason behind this is that longer retention times allow methanogenic bacteria to fully utilize the available organic substrates, completing the biochemical degradation processes necessary for maximum methane production. However, while a longer HRT improves biogas quality and quantity, practical considerations such as digester size, operational costs, and substrate availability must be taken into account when optimizing the retention time for large-scale applications. From an engineering perspective, an HRT of 30 days appears to be the most effective for maximizing biogas production while maintaining a high methane content. However, this may not always be economically feasible, as longer retention times require larger digestion tanks, increased capital investment, and potentially higher maintenance costs. In practical biogas plant operations, a balance must be found between achieving high methane yields and maintaining cost-effective and space-efficient digester systems. In conclusion, this study demonstrates that hydraulic retention time plays a vital role in optimizing biogas production. Longer retention times improve methane yield, decrease carbon dioxide levels, and create a more stable anaerobic environment, ultimately enhancing the efficiency and sustainability of anaerobic digestion processes. However, the ideal HRT should be selected based on specific project constraints, ensuring an optimal trade-off between biogas yield, system efficiency, and economic feasibility.

3.2 Effect of pH on biogas production

Table 3. Effect of pH on biogas production at HRT 30 day at 1.0 biogas volume (m³/kg.VS)

pH	Biogas volume (m ³ /kg.VS)	Methane content (%)
6.0	1.0	63.78
7.0	1.0	66.32
8.0	1.0	70.59
9.0	1.0	73.46

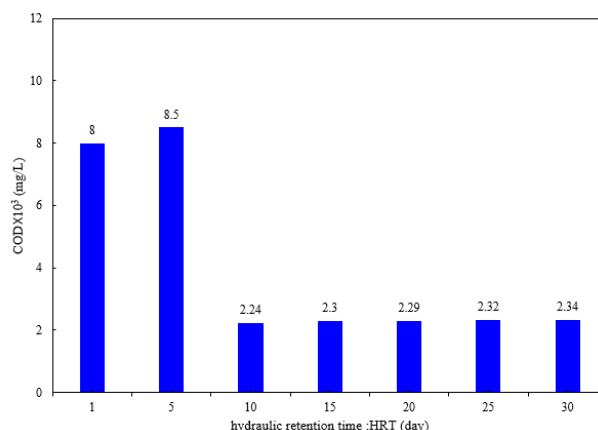
The experiment investigates the effect of pH on biogas production, focusing on both biogas volume and methane content under a hydraulic retention time (HRT) of 30 days. The result showed that the biogas volume remains constant at 1.0 m³/kg.VS across all tested pH levels (6.0, 7.0, 8.0, and 9.0), while the methane content progressively increases from 63.78% at pH 6.0 to 73.46% at pH 9.0. These findings provide insight into the role of pH in the anaerobic digestion process and methane production. Biogas production is a multi-stage biological process involving hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage is carried out by different microbial communities that thrive in specific pH ranges. Hydrolysis and acidogenesis, the initial stages of anaerobic digestion, are typically more active under slightly acidic conditions (pH 5.5–6.5), where hydrolytic and acidogenic bacteria break down complex organic matter into simpler organic acids. However, the final stage, methanogenesis, where methane-producing archaea convert intermediates into methane and carbon dioxide, occurs optimally in neutral to slightly alkaline conditions (pH 7.0–9.0). The experimental results indicate that the total biogas volume is not significantly affected within the pH range of 6.0 to 9.0, suggesting that the anaerobic digestion process remains stable across these conditions. However, the methane content shows a clear increasing trend with higher pH values. This observation suggests that methanogenic activity is more efficient under alkaline conditions. At lower pH levels, the accumulation of volatile fatty acids (VFAs) may inhibit methanogenesis, leading to lower methane yields. As the pH increases towards the alkaline range, methanogens become more active and efficient in converting intermediate organic compounds into methane, resulting in higher methane content in the biogas. The increase in methane content from 63.78% at pH 6.0 to 73.46% at pH 9.0 implies that slightly alkaline conditions favor methane production, enhancing the quality of the biogas. This is consistent with previous studies indicating that methanogenic archaea prefer neutral to slightly alkaline conditions and that pH imbalances can significantly impact methane yield. The improvement in methane content at higher pH levels suggests that buffering the pH towards alkalinity could be beneficial for optimizing biogas production, particularly in systems where methane quality is a priority. From a practical perspective, maintaining an optimal pH range is crucial for efficient biogas production. While the total biogas yield remains unchanged, a higher methane content enhances the energy value of the biogas, making it a more efficient fuel source. In industrial applications, controlling pH through buffering agents, such as sodium bicarbonate or lime, can help stabilize the anaerobic digestion process and maximize methane production.

However, excessively high pH levels beyond the tested range might start inhibiting microbial activity, which requires careful monitoring. Overall, the findings confirm the importance of pH regulation in anaerobic digestion. While biogas production remains stable across a wide pH range, methane production is significantly influenced by pH, with higher values favoring methanogenic activity. These results reinforce the theoretical understanding that methanogenesis is optimized under slightly alkaline conditions, highlighting the need for proper pH control in biogas systems to enhance methane yield and improve energy efficiency.

3.3 Effect of Chemical oxygen demand (COD) with HRT of biogas production

As shown in Figure 3, the chemical oxygen demand (COD) concentration was high during the initial stage of fermentation, with a value of 8.0×10^3 mg/L at an HRT of 1 day, increasing to a maximum of 8.5×10^3 mg/L at an HRT of 5 days. This indicates the presence of a large amount of biodegradable organic matter in the biogas production system. Thereafter, the COD concentration decreased markedly with increasing fermentation time, reaching values between 2.24 and 2.34×10^3 mg/L at HRTs of 10–30 days. This trend demonstrates the effective degradation of organic matter by anaerobic microorganisms during the digestion process.

The COD removal efficiency was further evaluated based on the observed data. The COD concentration decreased from 8.5×10^3 mg/L to an average value of 2.29×10^3 mg/L, corresponding to a COD removal efficiency of approximately 73.1%. Similarly, when comparing the initial COD concentration at day 1 (8.0×10^3 mg/L) with the minimum COD value recorded (2.24×10^3 mg/L), the COD removal efficiency was calculated to be 72.0%. Therefore, the overall COD removal efficiency of the biogas production system ranged from 72.0% to 73.6%, indicating a high level of treatment performance and demonstrating the effectiveness of anaerobic digestion in reducing the organic load within the system. The substantial reduction in COD observed between HRTs of 5 and 10 days suggests that this period represents the most active phase of microbial degradation. During this stage, readily biodegradable organic compounds were intensively consumed by anaerobic microorganisms and converted into intermediate products and biogas. After an HRT of 10 days, the COD concentration remained relatively stable, indicating that the system had reached a steady-state condition and that most of the remaining organic matter was less biodegradable. These findings suggest that an HRT of at least 10 days is sufficient for effective organic matter degradation and stable biogas production. At this retention time, more than 70% of the initial COD was removed, and the digestion system achieved operational stability. Extending the HRT beyond 10 days resulted in only minor additional reductions in COD, implying that longer retention times may not provide significant benefits in terms of treatment efficiency or economic feasibility.

**Figure 3.** COD value with with HRT of biogas production

3.4 Thermal efficiency of biogas

The test to determine the heating value and thermal efficiency of the produced biogas was conducted using the heating value and thermal efficiency of the produced biogas were evaluated using the Boiling Water Test (BWT) method. The recorded values were then used for calculations, including the initial and boiling water temperatures, as well as the initial and final water volumes. These data were applied in the equation (7) to calculate the heating value and thermal efficiency of the biogas. From the equation, the average heating value of the biogas was determined, as shown in Table 4.

Table 4. Thermal efficiency of biogas at HRT 30 day at 1.0 biogas volume ($\text{m}^3/\text{kg.VS}$)

pH	Methane content (%)	Heating value (kJ/kg)	η (%)
6.0	63.78	1,150.25	46.5
7.0	66.32	1,287.34	52.17
8.0	70.59	1,457.60	59.31
9.0	73.46	1,780.25	64.35

The table presents the thermal efficiency of biogas production at a hydraulic retention time (HRT) of 30 days under different pH conditions, with a fixed biogas production volume of $1.0 \text{ m}^3/\text{kg.VS}$. Key parameters measured include methane content, heating value, and thermal efficiency (η). The result showed that, it is evident that as the pH increases from 6.0 to 9.0, the methane content of the biogas also increases, ranging from 63.78% at pH 6.0 to 73.46% at pH 9.0. This trend directly influences the heating value, which rises from 1,150.25 kJ/kg to 1,780.25 kJ/kg. Consequently, the thermal efficiency improves significantly, reaching the highest value of 64.35% at pH 9.0. These results align with the principles of anaerobic digestion, where pH plays a critical role in microbial activity. Methanogenic bacteria, responsible for methane production, thrive in a slightly alkaline environment, typically between pH 6.8 and 8.5. As the

pH moves toward the upper end of this range, methane-producing microbes become more active, leading to increased methane concentration and energy output. In summary, the data suggest that controlling the pH toward the alkaline range, particularly around pH 8.0 - 9.0, enhances the quality of biogas by increasing its methane content and thermal efficiency. This highlights the importance of pH management in optimizing biogas production systems.

4. Conclusion

The results demonstrated that both hydraulic retention time (HRT) and pH significantly influenced biogas composition, methane concentration, and overall biogas quality. Increasing HRT from 10 to 30 days enhanced biogas production from 0.6 to 1.0 m³/kg VS, while methane concentration increased from 54.71% to 65.92%. Concurrently, carbon dioxide concentration decreased from 37.89% to 31.38%, indicating a more efficient methanogenesis process and improved conversion of organic matter into methane. The reduction in oxygen and nitrogen concentrations further confirmed the establishment of stable anaerobic conditions within the digester, minimizing air intrusion and promoting the activity of methanogenic microorganisms. The COD analysis supported these findings, showing that organic matter degradation occurred primarily during the first 10 days of digestion. COD concentrations decreased from 8.0–8.5 × 10³ mg/L to approximately 2.24–2.34 × 10³ mg/L, corresponding to a removal efficiency of 72.0–73.6%. The stabilization of COD after 10 days the result showed that most readily biodegradable organic compounds had been consumed and converted into biogas. Consequently, an HRT of at least 10 days was necessary to achieve effective substrate degradation and stable methane production. The effect of pH on biogas quality was also pronounced. Although the biogas yield remained constant at 1.0 m³/kg VS at an HRT of 30 days, methane concentration increased substantially from 63.78% at pH 6.0 to 73.46% at pH 9.0. This improvement was accompanied by an increase in heating value from 1,150.25 kJ/kg to 1,780.25 kJ/kg and a maximum thermal efficiency of 64.35% at pH 9.0. The enhanced methane production under alkaline conditions can be attributed to the favorable environment for methanogenic archaea and the reduced inhibitory effects of volatile fatty acids (VFAs).

Overall, the highest biogas quality was achieved at an HRT of 30 days and pH 9.0, yielding a methane concentration of 73.46%, a heating value of 1,780.25 kJ/kg, and a thermal efficiency of 64.35%. These results indicate that methane concentration is a key indicator of biogas quality, directly affecting its energy content and thermal performance. Therefore, maintaining an appropriate HRT and controlling pH within the slightly alkaline range (8.0–9.0) are critical factors for maximizing methane production, improving biogas quality, and enhancing the overall efficiency of anaerobic digestion systems.

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6. Consent to Participate, and Consent to Publish

Ethics, Consent to Participate, and Consent to Publish declarations

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