Leaves to Energy: A Comprehensive Study on Biogas Production from Fallen Leaves

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A Thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Industrial and Production Engineering[1] & Mechanical Engineering[2]

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, **"Leaves to Energy: A Comprehensive Study on Biogas Production from Fallen Leaves"**, is the outcome of the investigation and research carried out by me under the supervision of **PROF.DR.MD.HAMIDUR RAHMAN, Professor, MPE, IUT.** It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Abstract

An experimental inquiry into the production of biogas from fallen leaves gathered on Islamic University of Technology (IUT) campus is presented in this paper. Five distinct leaf species were chosen as biogas production substrates: Artocarpus heterophyllus (jackfruit), Swietenia macrophylla (mahogany), Mangifera indica (mango), Syzygium cumini (java plum) and Tectona grandis (teak). The leaves were chopped and combined with water to form a slurry in an anaerobic digester, which started the anaerobic digestion process. Gas composition analysis was used to validate the production of methane. The study compared the amount of methane produced by freshly fallen leaves to that of dried leaves. It also looked into how cow dung affected the ratio of carbon to nitrogen (C/N), how calcium carbonate ($CaCO_3$) affected the amount of methane produced, and how much CO_2 and H_2S was present in the biogas. The results were consistent and the possibility of employing fallen leaves as a biogas substrate, underscores the complexity of the process and areas that require additional improvement. Jackfruit leaves have been shown to produce significant amounts of methane; samples have been shown to produce up to 29.67% methane. This is explained by the leaves' high cellulose and carbohydrate content, ideal C/N ratio, and readily degradable structure. A 60-day reanalysis of the samples revealed a rise to 35% in methane output. There was also little H_2S formation (<0.1ppm) and a drop in the CO_2 proportion as methane production rose. However, methane was not created by green leaves. The study highlights the advantages of using fallen leaves to produce biogas, including how it can lower greenhouse gas emissions, offer a sustainable energy source, and improve waste management on the IUT campus. However, it also notes some of the difficulties that may arise. Important areas for additional investigation were differences in leaf content, possible anaerobic digestion process inhibitors, and the need for a better comprehension of the variables impacting biogas production.

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Nomenclature

Food Waste	FW
Cow Dung	CD
Food and Agriculture Organization	FAO
Islamic University of Technology	IUT
Municipal Solid Waste	MSW
Anerobic Digestion	AD
Volatile Fatty Acid	VFAs
Total Solid	TS
Volatile Solid	VS

Chapter One: Introduction

1.1 Background of the study

Recently, research into generating biogas from organic waste materials has increased, offering a practical solution for the disposal of waste and the generation of clean energy. Even though many organic waste materials have been studied in great detail, leaves that have fallen still represent an untapped potential feedstock for the production of biogas. The purpose of this study is to assess biogas generation from fallen leaves experimentally, with an emphasis on the impact of different process variables on biogas yield.

The global shift from fossil fuel-based economies to biofuel-based ones is mostly driven by the environmental effect and rising cost of fossil fuels. This change is a part of a larger plan, as discussed at international gatherings like COP26, to add 5.4 terawatts (TW) of renewable energy capacity by 2030. To achieve this, countries all across the world have set aggressive targets for renewable energy. For example, Bangladesh's Nationally Determined Contribution (NDC) calls for the country to reach a target of 4,100 MW of renewable energy capacity by 2030.

Here, leaves that have fallen offer a special chance to be used as a feedstock for biogas. Plants and trees naturally lose their leaves as a result of different seasonal variations, environmental factors, and tree health. Droughts, severe temperatures, and pest infestations are some of the factors that cause leaves to fall. Furthermore, deciduous trees shed their leaves in order to save energy for the upcoming winter. As a result of this natural process, a large and frequently underutilized biomass resource is produced that can be used to produce biogas and help countries meet their targets for renewable energy.

Falling leaves can be used as a sustainable biogas feedstock, which could lead to improved waste management and sustainable production of renewable energy. This strategy is in line with international initiatives to attain energy security, lessen the impact on the environment, and lessen dependency on fossil fuels. The overall goals of international agreements like those signed at COP26 are supported by the inclusion of biofuels in the energy mix, which encourages a cleaner, more sustainable future. Anaerobic digestion is generally acknowledged that the best technique for turning biomass—including leaves—into methane is anaerobic digestion. The major stages of this oxygen-free biological process include acetogenesis, methanogenesis, hydrolysis, and acidogenesis. Complex organic substance is hydrolyzed to produce simpler soluble molecules. These substances undergo further breakdown into volatile fatty acids, alcohols, hydrogen, and carbon dioxide during the acidogenesis phase by acidogenic bacteria. Acetogenic bacteria use acetogenesis to transform volatile fatty acids and alcohols into acetic acid, hydrogen, and carbon dioxide. Lastly, methanogenic archaea produce methane and water during the methanogenesis phase by converting acetic acid, hydrogen, and carbon dioxide. The resulting biogas, which is mostly made up of carbon dioxide (CO_2) and methane (CH_4), can be used to produce heat or power, making it a useful renewable energy source.

Co-digestion, which is the process of combining various organic wastes in an anaerobic digestion system, has a number of important advantages over conventional techniques. Co-digestion has the potential to improve process stability and boost methane generation by processing a variety of organic wastes. This can be attributed in large part to the synergistic effects of combining substrates with complimentary properties, which can enhance the digester's microbial activity and nutritional balance. Moreover, co-digestion might lessen the difficulties posed by mono-digestion of particular feedstocks, which may contain chemicals that block digestion or be lacking in key nutrient.

Anaerobic digestion also has benefits for the environment and the economy. It offers an affordable waste management solution by lowering the expenses related to the disposal of organic waste. This is especially crucial for businesses and governments trying to manage garbage in an environmentally friendly way. Furthermore, co-digestion lessens the need for fossil fuels and greenhouse gas emissions by expanding the pool of renewable energy sources. To further enhance its environmental benefits, the produced biogas can be converted to biomethane, which can then be used as vehicle fuel or fed into the natural gas grid.

1.2 Statement of the problem

The disposal of fallen leaves in Bangladesh is difficult, especially in metropolitan areas where burning increases air pollution and public health risks. Innovative approaches are crucial to meeting the nation's energy and waste management needs. The conversion of falling leaves into biogas is promising. This study investigates the feasibility and efficacy of this strategy in Bangladesh. The research optimizes anaerobic digestion procedures to understand conversion mechanisms and efficiencies for environmental and economic benefits. The project aims to demonstrate biogas production from falling leaves as a holistic option. It assesses urban leaf kinds to determine the best anaerobic digestion conditions for biogas production. The research also evaluates urban waste management system scalability for widespread application. This study aims to push Bangladesh toward sustainable waste management and energy production by examining environmental and economic benefits, such as reduced air pollution and greenhouse gas emissions and cost savings.

1.3 Goals and Objectives

- Comparing the methane production from freshly fallen leaves and dried leaves.
- Studying the effects of Cow Manure used to control C/N ratio.
- Studying the impact of CaCO3 on methane Production.
- Comparing the production of Biogas between different plant leaf types.
- Compare CO2 and H2S gas percentage and assess its impacts on the environment.

1.4 Limitations of the Study

- Seasonal availability poses a challenge for consistent fallen leaf supply.
- Variations in feedstock composition impact anaerobic digestion efficiency.
- Inhibitory substances in fallen leaves may hinder overall biogas production.
- Evaluating economic viability is essential, considering collection and processing costs.
- Scaling up fallen leaf biogas production requires careful consideration of efficiency.
- Adequate infrastructure, including anaerobic digesters, is crucial for successful implementation.

Chapter 2: Literature Review

2.1 Anaerobic Digestion

Anaerobic digestion, a biological process, is essential to sustainable waste management and renewable energy. This complex process uses microbes to break down organic materials into biogas, mostly methane and carbon dioxide, without oxygen. Anaerobic digestion can handle agricultural wastes, food waste, and sewage sludge due to its adaptability. Anaerobic digestion minimizes environmental impacts of typical waste disposal while creating renewable energy. Optimizing operational parameters including temperature, pH, and retention time is key to anaerobic digestion performance. Microbial activity and biogas output are optimized by fine-tuning these variables. Research has examined the complex relationship between these factors and anaerobic digester microbial communities. Anaerobic digestion processes are optimized and applied to diverse waste management settings using insights from such investigations. Anaerobic digestion can improve energy security and climate change beyond waste management. Biogas from anaerobic digestion reduces fossil fuel consumption and greenhouse gas emissions, improving environmental sustainability. Biogas from anaerobic digestion can be used to generate electricity, heat, or transport fuel with a reduced carbon footprint than fossil fuels.

2.2 Biogas from fallen leaves

2.2.1. Feedstock Characteristics:

Fallen leaves are rich in lignocellulosic materials, comprising cellulose, hemicellulose, and lignin. These complex polymers serve as ideal substrates for microbial digestion, contributing to the efficient production of biogas. The composition of fallen leaves, however, varies depending on the tree species, geographical location, and seasonal factors. Understanding these variations is crucial for optimizing the biogas production process and enhancing overall efficiency.

2.2.2. Microbial Processes:

Microbial degradation of fallen leaves in anaerobic conditions plays a pivotal role in biogas production. Various microorganisms, including bacteria, archaea, and fungi, collaborate in a complex process of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Studies have focused on identifying and optimizing microbial communities for enhanced biogas yields, with an emphasis on microbial consortia capable of breaking down recalcitrant components present in fallen leaves.

Hydrolysis: The hydrolysis process in anaerobic digestion can be represented by the following general reaction:

Complex organic compounds + Water→ Simple organic compounds + Enzymes

Complex organic molecules including carbohydrates, proteins, and lipids in organic waste react with water in the presence of microbial hydrolytic enzymes. Large organic molecules are broken down into sugars, amino acids, and fatty acids by these enzymes. Enzymatic hydrolysis breaks chemical bonds in complicated substrates, creating smaller bits that are easier to degrade by microbes. Anaerobic digestion works best when the hydrolysis step breaks down complex organic matter into soluble intermediates that microbial metabolism can use. Methane-rich biogas is produced by fermentative bacteria and methanogenic archaea absorbing these soluble components from the solution. The hydrolysis reaction is essential to anaerobic digestion, breaking down complex organic compounds and enabling biogas production from organic waste.

Acidogenesis: Acidogenesis, following hydrolysis and preceding acetogenesis, is crucial to anaerobic digestion. Acidogenic bacteria convert hydrolyzed organic substances into VFAs, alcohols, and other small molecules during acidogenesis. Fermentation, decarboxylation, and hydrogenation are used in this acidic biochemical reaction. Acetic acid, propionic acid, and butyric acid are key substrates for acetogenesis and methanogenesis in anaerobic digestion. Acidogenesis also stabilises digestion by avoiding inhibiting chemicals and maintaining an appropriate pH range for microbial action. Ethanol, acids (propionic and butyric), acetate, H_2O, and CO_2 are produced by microbes fermenting carbohydrates and amino acids into soluble organic monomers. In addition to hydrogen gas, amino acid breakdown produces ammonia. Acidogenic bacteria use their cell membranes to absorb hydrolysis byproducts to create intermediate volatile fatty acids (VFAs) and other compounds. Volatile fatty acids (VFAs) contain both smaller and bigger organic acids, such as acetates and propionate and butyrate. Daily living often involves ratios between 75 and 15 to 10. Trace amounts of ethanol and lactate may remain detectable. Different study suggests that intermediate concentrations during acidogenesis may vary based on digester settings, and VFA concentrations may vary considerably across digesters at different pH levels. Acidogenic bacteria can reproduce in less than 36 hours, leading to the assumption that acidogenesis occurs faster than other stages of anaerobic digestion. VFA acidification is often the cause of digester failure due to its rapid development. Final stage: methanogenesis. The process involves the production of naturally occurring volatile fatty acids (FFAs) during fermentation. The bacteria used in this approach break down trash similarly to the Bokashi composting method. Deaminating amino acids to ammonia slows anaerobic digestion.

Acetogenesis: During the anaerobic digestion process known as acetogenesis, carbon molecules like sugars and organic acids are broken down by microbes into acetate, hydrogen, and carbon dioxide. Usually, acetogens—a class of microorganisms—are responsible for this process.

Acetogenesis involves a number of primary reactions, which include:

1. The process of acidogenesis, which transforms carbohydrates like glucose into organic acids like acetic acid.
2. The acetogenesis process, which turns organic acids like acetic acid into acetate.
3. The process of methanogenesis, which turns hydrogen into methane.

The following equation can be used to depict the overall acetogenesis reaction:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

This equation describes how the process of acidogenesis transforms glucose ($C_6H_{12}O_6$) into acetic acid (CH_3COOH) and carbon dioxide (CO_2). The process of acetogenesis then transforms acetic acid into acetate (CH_3COO-), hydrogen, and carbon dioxide. It is important to remember that acetogens are the only organisms that can change acetic acid into acetate, which makes them essential to the entire anaerobic digestion process. Furthermore, methanogens can use the hydrogen created during acetogenesis to make methane, a useful energy source, during the methanogenesis process.

Methanogenesis: The final stage of the process, which entails converting acetic acid and hydrogen into methane gas and carbon dioxide, is carried out by methanogenic bacteria. Temperature, feed content, and organic loading rate are only a few of the reactor's properties that have an impact on methanogenesis. Methane (CH_4) and carbon dioxide (CO_2) make up the majority of biogas, but it also contains nitrogen, oxygen, and hydrogen. It is hydrogen sulfide, or H_2S, that gives off the rotten egg stench. Combustible biogas needs to contain at least 45% methane since the gas has higher energy when there is more CH_4. The final step in anaerobic digestion is the synthesis of methane by methanogenic bacteria. A requirement for anaerobic archaea, like methanogenic bacteria, 99 percent of whose cells perish in the presence of oxygen in just 10 hours. Methanogenic bacteria have high sensitivity to oxygen and exhibit substrate selectivity. Formates, methylamines, and methanol have also been observed to be used in methanogenesis. It is anticipated that methanogenic bacteria will have a lower redox potential than they did during the initial phases of anaerobic digestion, which has caused serious challenges with laboratory culture. Methanogens appear to recover far more slowly than other species. Without oxygen, anaerobic bacteria can survive for five to sixteen days. Methanococcus maripaludis is a good example of a fast-growing hydrogenotrophic bacterium; in less than two hours, its population can quadruple. Methanosarcina spp. have demonstrated extreme resilience to environmental factors such as high concentrations of ammonia, salt, and acetate as well as quick pH changes. Methanogenesis is halted in batch reactors by reducing the biogas output, which can take up to 40 days. Two metrics can be used to evaluate the digested sludge's quality: the concentration of volatile solids and its dewaterability.

Anaerobic digestion culminates in the methanogenesis pathway. These operations generate the byproducts of a number of reactions, the most significant of which is the production of methane. During methanogenesis, the most frequent reactions are as follows:

$$2CH_3CH_2OH + CO_2 \rightarrow CH_3COOH + CH_4$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$CH_3OH \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

It is noteworthy that methanogenesis is facilitated by a wide variety of bacteria, not just Methanobacterium, Methanobacillus, Methanococcus, and Methanosarcina. Anaerobic digestion Bacteria are distinct from other enzymes that produce biofuel because they may be residents in our own digestive systems. A vast range of organic resources, such as plant biomass, food wastes, green wastes, sewage sludge, and manure and litter, can be fed into anaerobic digesters. To decompose cellulose and Hydrolysis is the rate-limiting stage in the disintegration of hemicellulose, two chemical components that disintegrate incredibly slowly. Lignin is one example of a chemical substance that the body is unable to break down. Proteins linked to membranes and peptidoglycan. We have demonstrated that pretreatment of biomass before ethanol synthesis can potentially boost anaerobic digestion efficiency.

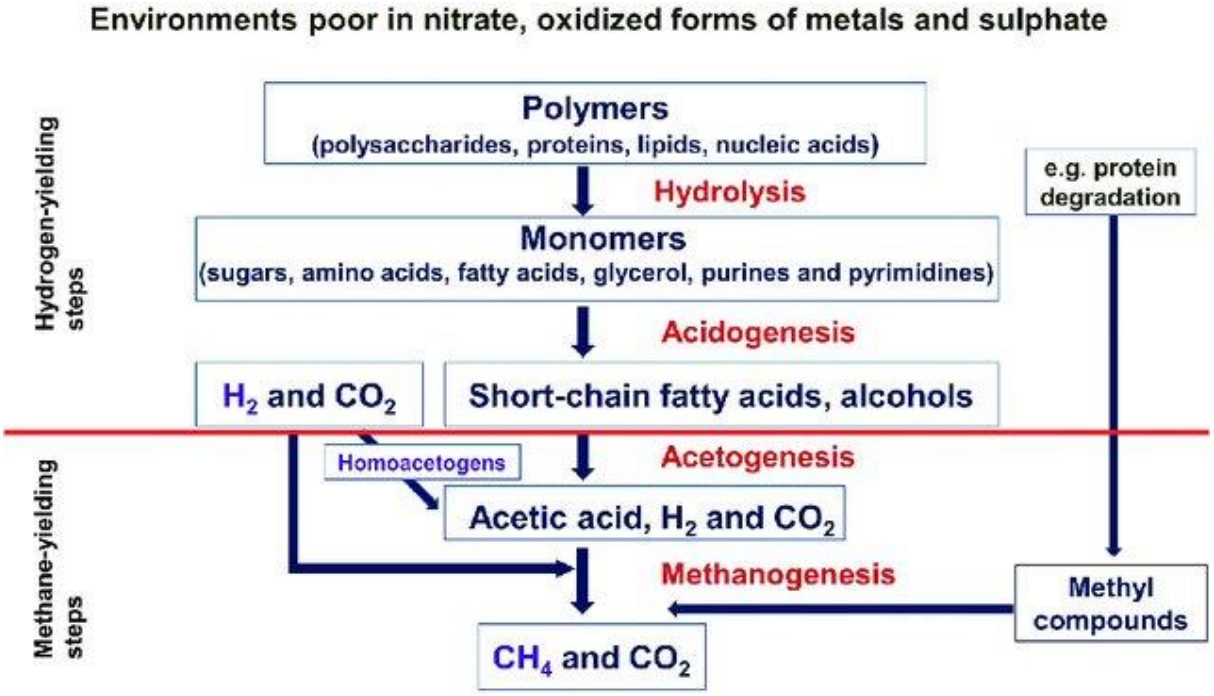


Figure 1: Production of methane from organic matter

2.2.3. Process Optimization:

Optimizing the biogas production process from fallen leaves involves addressing factors such as temperature, pH, and nutrient balance. Researchers have explored the impact of different pretreatment methods, such as thermal, chemical, or biological processes, to enhance the accessibility of fallen leaves to microbial activity. Additionally, advancements in reactor design and configuration, such as continuous stirred-tank reactors (CSTRs) and anaerobic baffled reactors (ABRs), have been investigated to improve biogas production rates and stability.

2.2.4. Thermal Pretreatment:

Anaerobic digestion requires a pre-conditioning phase called thermal pretreatment, which entails heating organic waste products to a high temperature in order to prepare them for digestion. The goal of this procedure is to break up complicated organic molecules into smaller pieces so that microorganisms can break them down more easily and produce more biogas more efficiently. Organic substrates are heated during thermal pretreatment, usually under pressure to prevent vaporization, to temperatures between 70°C and 160°C for a predetermined amount of time. The organic material undergoes physical and chemical changes as a result of this heat exposure, including the disintegration of microbial cells and enzymes, the solubilization of organic materials, and the breakdown of cellulosic and lignocellulosic structures.

Increased organic compound solubilization, higher hydrolysis rates, and improved breakdown of resistant materials are some advantages of heat pretreatment. Thermal pretreatment can also lead to shorter digestion times, higher biogas production, and more stable processes. Heating the organic feedstock during thermal pretreatment incurs energy and operating costs. Moreover, overheating can cause inhibitory compounds to form or volatile organic matter to be lost, which can affect the efficiency of the process as a whole.

The utilization of heat pretreatment has the potential to boost the effectiveness of anaerobic digestion by increasing the organic substrates' accessibility and degradability. To optimize thermal pretreatment conditions and determine its viability and economics for various waste streams and anaerobic digestion systems, more investigation and optimization work are required.

2.2.5. Environmental and Economic Impacts

Biogas production from fallen leaves has the potential to offer multiple environmental and economic benefits. The utilization of a readily available waste stream not only helps in waste management but also reduces greenhouse gas emissions and dependence on fossil fuels. Additionally, the production of biogas can contribute to rural development by providing decentralized energy solutions and fostering sustainable practices.

The literature on biogas production from fallen leaves reflects a growing interest in harnessing this renewable energy source. Ongoing research efforts focus on improving feedstock characteristics, understanding microbial processes, optimizing operational parameters, and addressing challenges associated with scalability and economic feasibility. As technology continues to advance, the integration of fallen leaves into biogas production processes holds great promise for sustainable energy generation and environmental conservation. Further interdisciplinary research and collaboration are essential to unlock the full potential of fallen leaves as a valuable resource in the pursuit of a more sustainable energy future.

2.3 Effect of $CaCO_3$ addition on anaerobic digestion's ability to produce methane

The addition of calcium carbonate ($CaCO_3$) to anaerobic digestion can have several effects on the process's ability to produce methane. These effects include pH stabilization, buffering capacity, precipitation of inhibitory substances, and microbial activity modulation. Here’s a detailed explanation:

2.3.1. pH Stabilization and Buffering Capacity:

Anaerobic digestion is sensitive to pH fluctuations, with optimal methane production typically occurring at a pH range of 6.8 to 7.2. The addition of $CaCO_3$ helps stabilize the pH by acting as a buffer. When organic acids are produced during digestion, they can lower the pH, inhibiting methanogenic bacteria. $CaCO_3$ reacts with these acids, neutralizing them and preventing significant pH drops, thereby maintaining an environment conducive to methane production.

2.3.2. Precipitation of Inhibitory Substances:

Certain substances, such as sulfides and heavy metals, can inhibit microbial activity in anaerobic digestion. $CaCO_3$ can precipitate these inhibitory substances as insoluble compounds (e.g., $CaSO_4$ for sulfides). By removing these inhibitors from the liquid phase, $CaCO_3$ can enhance microbial activity and methane production.

2.3.3. Enhanced Microbial Activity:

Methanogens, the microorganisms responsible for methane production, thrive in environments with stable pH and minimal toxic substances. By providing a stable pH and reducing toxicity, $CaCO_3$

creates favorable conditions for methanogens, potentially increasing their activity and the overall methane yield.

2.3.4. Nutrient Availability:

$CaCO_3$ can also contribute to the availability of essential nutrients. Calcium ions are necessary for certain microbial enzymatic activities. By supplying these ions, $CaCO_3$ can indirectly support the metabolic activities of various microbial populations involved in the anaerobic digestion process.

Empirical Evidence:

Several studies have demonstrated the positive impact of $CaCO_3$ on methane production:

- **Buffering Capacity:** Research shows that the addition of $CaCO_3$ enhances the buffering capacity of the digester, maintaining a stable pH which is critical for methanogenic activity.
- **Methane Yield Improvement:** Experimental results often indicate an increase in methane yield when $CaCO_3$ is added, attributed to the improved stability of the anaerobic digestion process.
- **Precipitation of Inhibitors:** Studies confirm that $CaCO_3$ can precipitate sulfides and other inhibitory substances, thus reducing their negative impact on microbial activity.

Optimal Dosage:

The optimal dosage of $CaCO_3$ varies depending on the feedstock and the specific conditions of the anaerobic digester. Excessive addition can lead to an increase in the solids content and potential operational issues, such as clogging. Therefore, it's crucial to determine the appropriate amount through pilot studies or laboratory-scale experiments to maximize the benefits without causing adverse effects.

2.4 Operational parameters

2.4.1. Temperature

Mesophilic microorganisms grow best at temperatures between 30 and 40 degrees Celsius, while anaerobic bacteria prefer 37 degrees Celsius. In mesophilic conditions, bacteria and archaea thrive between 30 and 40 degrees Celsius, while in thermophilic habitats, they grow above 60 degrees Celsius (optimum temperature: 55 degrees Celsius). At mesophilic temperatures, digesters work more effectively because the microbial communities there are less energy-hungry and more adaptable to changes in their environment. Ammonium's effect is lessened at lower temperatures since there is less ammonia present. More biogas will be produced if mesophilic bacteria have more time to develop in the digester. More than 50% faster breakdown is possible due to thermophilic activity, which is especially advantageous for fatty compounds. As a result, more biogas is generated. Because CO_2 becomes less soluble at higher temperatures, biogas in thermophilic digesters has a 2-4% rise in CO_2 content. Although there may be some advantages to operating the digester at thermophilic temperatures, the additional energy requirements and instability render it unfeasible for application in developing nations.

2.4.2. pH

Most AD plants that produce a significant amount of biogas are stable at pH values of 6–7. After digestion, acidogenesis takes place at a lower pH (5.5–6.5), in contrast to methanogenesis, which happens at a higher pH (>6.5). (6.5–8) At all times, 3,000 mg/L of buffering capacity is needed.

In AD systems, lime is frequently added to increase the pH if it is too low. On the other side, the pH level can be changed using sodium bicarbonate. If they have an excess of lime, some local businesses might even give it away. Generally speaking, lime is less expensive than other building materials. The two most common undesirable effects of lime are pipe obstruction and precipitation. Because neither sodium hydroxide nor sodium bicarbonate ever precipitate, costs are higher. Sodium hydroxide and sodium bicarbonate may be more difficult to find than lime. Na salts are advised for immediate comfort. Lime can be used as a backup pH adjuster.

Chapter 3: Methodology

3.1 Leaves Collection

Fallen leaves were collected from diverse locations at the IUT campus. Jackfruit and java plum leaves were found near the workshop, while leaves from mango, teak, and mahogany trees were collected from the tree park. This diverse collection captures varied organic inputs from both dynamic and natural environments, providing a rich and representative substrate for biogas production.

Figure 2: IUT Campus Outline

3.2 Leaves Processing

The leaves were collected and kept to dry for 3 days. After the moisture or any exterior water particle dried up, the leaves were mashed using a blender. The leaves were grounded. The fine size of the particles will allow the bacteria to have greater contact area thus better digestion.

Figure 3: Collected leaves after drying

Figure 4: Leaves Processing with Blender

3.3 Temperature Control

An incubator setup was used to control the temperature. The setup included light bulbs and a temperature controller called a W1209. The controller was set to keep the temperature at 37 degrees Celsius. Once the temperature reached 37 degrees, the light bulbs would turn off. If the temperature dropped to 36.5 degrees, the light bulbs would turn back on and stay on until the temperature reached 37.5 degrees. The inside of the setup was insulated to prevent heat from escaping. Once the desired temperature of 37 degrees was reached, the setups were placed inside a temperature-controlled box and left there for a certain amount of time.

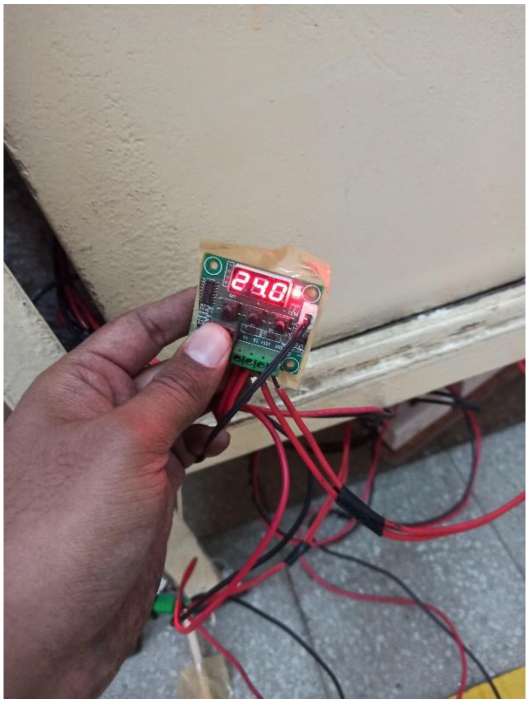


Figure 5: Temperature Controller

Figure 6: Incubator setup

3.4 Initial Setup

Figure 7: Initial setup of digesters

Single bottle setup was done to examine the presence of methane in the digester. Leaf samples of 50g with 500 mL solution and 10g $CaCO_3$ was mixed. The 500 mL solution was then transferred into 1L glass bottles. The glass bottles had a head with two outlets, one with ball valve and another with screw valve. The bottle was tightened and the air was removed using a vacuum pump. The plastic bottles were kept inside a black box at 37°. Gas chromatograph was used to analyze the gas and determine the percentage of different gases present in the digester. Gas samples were collected directly to the analyzer with the gas outlets of the bottle. Universal pH paper was used to monitor the pH of the solution during every reading.

Figure 8: Vacuuming of the digestors and keeping them in black box

3.5 Inoculum

Cow-dung was collected and kept in a plastic tank for 30 days for bacteria to grow. It was kept in a sealed tank under atmospheric condition. It allowed the bacteria to adapt to mesophilic condition. After 30 days, 5g cow-dung was mixed with the digester which was already under regular monitoring.

Figure 9: Measuring Cow-dung

3.6 Slurry Preparation

Initially 10 reactors were used to digest different leaves. Every reactor consisted 500ml water as solution. CaCO3 was added to maintain the C/N ratio and to maintain the pH levels.

Digester	Sample	Amount of $CaCO_3$	Inoculum
Reactor 1	50g Green Teak Leaves	10g	5g Cow-dung
Reactor 2	50g Green Mahagony Leaves	10g	5g Cow-dung
Reactor 3	25g Dry Teak Leaves 25g Green Mahagony Leaves	10g	5g Cow-dung
Reactor 4	50g Green Java plum Leaves	5g	5g Cow-dung
Reactor 5	50g Green and dried Jackfruit Leaves	5g	5g Cow-dung
Reactor 6	18g Dry Mahagony Leaves 18g Dry Teak Leaves 14g Dry Java Plum Leaves	5g	5g Cow-dung

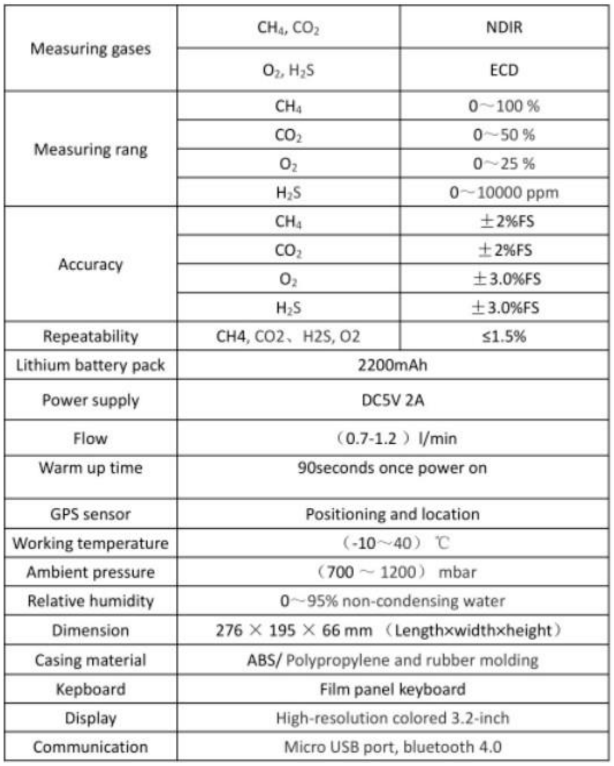
Reactor 7	50g Green Jackfruit Leaves	10g	10g Cow-dung
Reactor 8	25g Green Mango Leaves 25g Green Java Plum Leaves	10g	10g Cow-dung
Reactor 9	25g Green and dried Jackfruit Leaves 25g Dry Java Plum Leaves	10g	10g Cow-dung
Reactor 10	25g Dry Teak Leaves 25g Dry Java Plum Leaves	10g	5g Cow-dung

3.7 Gas Analyzing

Gasboard Analyzer-3200 Plus was used to analyze the gas at certain intervals

3.7.1 Gas Analyzer Specification

For monitoring anaerobic digestions projects, Gasboard analyzer-3200 plus is widely used. There are 4 different sensors, which are CH_4, CO_2, H_2S, O_2



Measuring gases	CH_4, CO_2	NDIR
	O_2, H_2S	ECD
Measuring rang	CH_4	0～100 %
	CO_2	0～50 %
	O_2	0～25 %
	H_2S	0～10000 ppm
Accuracy	CH_4	±2%FS
	CO_2	±2%FS
	O_2	±3.0%FS
	H_2S	±3.0%FS
Repeatability	CH4, CO2、H2S, O2	≤1.5%
Lithium battery pack	2200mAh	
Power supply	DC5V 2A	
Flow	（0.7-1.2 ）l/min	
Warm up time	90seconds once power on	
GPS sensor	Positioning and location	
Working temperature	（-10～40） ℃	
Ambient pressure	（700 ～ 1200） mbar	
Relative humidity	0～95% non-condensing water	
Dimension	276 × 195 × 66 mm （Length×width×height）	
Casing material	ABS/ Polypropylene and rubber molding	
Kepboard	Film panel keyboard	
Display	High-resolution colored 3.2-inch	
Communication	Micro USB port, bluetooth 4.0	

Figure 10: Gas Board 3200 Plus Specification

3.7.2 Data Collection

We were able to gather and store gas data using the companion software that came with the analyzer. A laptop was used to record and store the data. Microsoft Excel was used for the analysis and interpretation of it. The valve output of the arrangement was connected to the analyzer's input port. Scrubbers and air filters were used in between to keep the gasses free of pollutants. The analyzer's pump was activated and the toggle valve was gradually opened to let the gas produced in the bottle pass through the device.

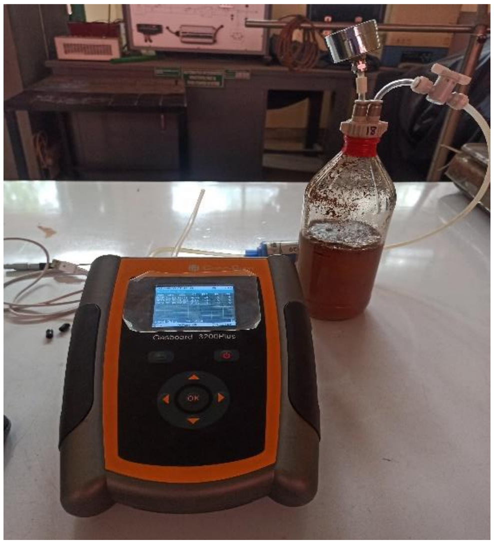


Figure 11: Measuring gas percentage with Gasboard analyzer

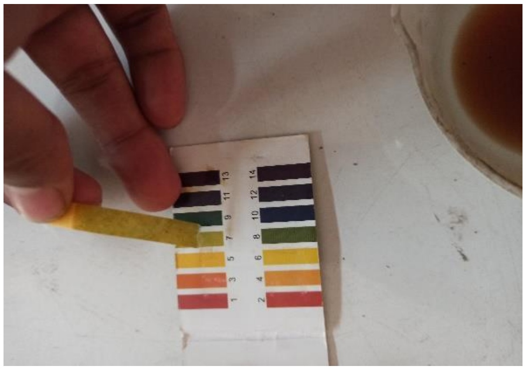


Figure 12: Measuring pH with universal pH paper

3.7.3 Verification of presence of methane

The methane production was tested by setting a flame at the gas outlet. Generally 60% methane rate is required to get flame. In our digesters, the highest methane rate was found to be 30.70% in reactor 5 but no flame was seen as the methane rate in the digesters was not enough to be flammable.

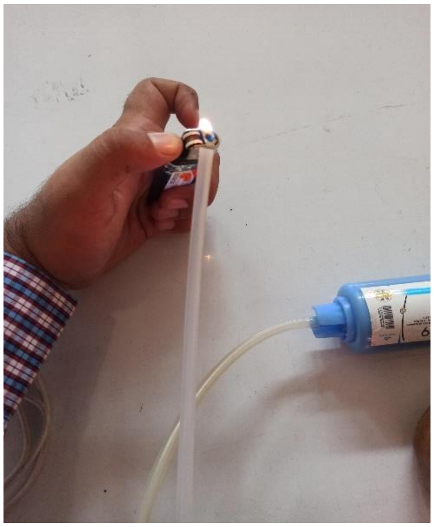


Figure 13: Flame test

3.8 New Setups

The second part of our experiment aimed to increase methane production efficiency by shortening the time needed to reach a 60% methane concentration. **Dried leaves** were chosen as the main substrate because they were readily available, had favorable methane production characteristics, and had a high rate of leaf litter.

To investigate the effects of different parameters on methane production, 10 new setups were designed.

Digester	Sample	Amount of $CaCO_3$	Inoculum
Reactor 11	25g Mahagony Leaves 25g Java Plum Leaves	10g	10g Cow-dung
Reactor 12	30g Mahagony Leaves 20g Java Plum Leaves	5g	5g Cow-dung

Reactor 13	50g Teak Leaves	10g	10g Cow-dung
Reactor 14	15g Mahagony Leaves 35g Jackfruit Leaves	5g	5g Cow-dung
Reactor 15	50g Jackfruit Leaves	10g	10g Cow-dung
Reactor 16	25g Jackfruit Leaves 25g Teak Leaves	15g	10g Cow-dung
Reactor 17	50g Jackfruit Leaves	15g	10g Cow-dung
Reactor 18	50g Jackfruit Leaves	20g	10g Cow-dung
Reactor 19	50g Jackfruit Leaves	25g	10g Cow-dung
Reactor 20	50g Jackfruit Leaves	30g	15g Cow-dung

Dry leaves were selected as substrate for the new setups. Dry leaves are generally better than green fallen leaves for methane production for a few key reasons:

Lower Moisture Content: Dry leaves have a lower moisture content compared to green leaves. High moisture content in green leaves can dilute the feedstock and reduce the efficiency of the anaerobic digestion process, making it less efficient for methane production.

Higher Carbon Content: Dry leaves typically have a higher carbon-to-nitrogen (C) ratio. Anaerobic digestion requires a balanced C ratio for optimal microbial activity. Green leaves tend to have higher nitrogen content, which can lead to ammonia accumulation and inhibit the digestion process.

Decomposability: Dry leaves, having undergone some degree of natural breakdown, may be more readily decomposed by the anaerobic bacteria. Green leaves contain more complex structures and chlorophyll, which can be more difficult for anaerobic bacteria to break down.

Reduced Inhibitory Compounds: Green leaves contain certain compounds (e.g., chlorophyll, tannins, phenols) that can be inhibitory to the microbes involved in methane production. These compounds are typically reduced or altered as leaves dry and decompose naturally.

Stability: Dry leaves are more stable and less prone to rapid decomposition and spoilage compared to green leaves, making them easier to store and handle before they are processed for methane production.

These factors make dry leaves a more efficient and effective feedstock for methane production in anaerobic digestion systems.

The experiment was conducted in anaerobic digesters maintained under controlled temperature and pH conditions. Methane production was monitored regularly using gas chromatography to assess the progress and efficiency of the anaerobic digestion process.

To quantify the methane concentration, samples were collected from the digesters at regular intervals and analyzed using established scientific methods. The methane production rate, time required to reach 60% methane concentration, and any observed variations or abnormalities in the biogas composition were recorded and analyzed.

In summary, the methodology involved the selection of green and dry leaves as the primary substrate, followed by the creation of 20 distinct setups, each exploring the effects of different parameters on methane production efficiency.

Chapter 4 Result and Discussion

4.1 Gas Analyzing Results

1. Low overall methane yield:

Out of 20 digesters, two (reactors 5 and 18) showed significant methane production. Sample 5 had a methane percentage of 29.67% and Sample 18 had 25.21%. The third highest methane rate was found in reactor 19 which was 12%.

This indicates that the overall process for these digesters needs improvement. There could be several factors affecting this, such as:

- Substrate type: The organic matter used in the digesters might not be ideal for methane production.
- Operating conditions: Temperature, pH, and nutrient balance might not be optimal for the methanogenic bacteria.
- Microbial community: The specific bacteria present in the digesters might not be efficient methane producers.

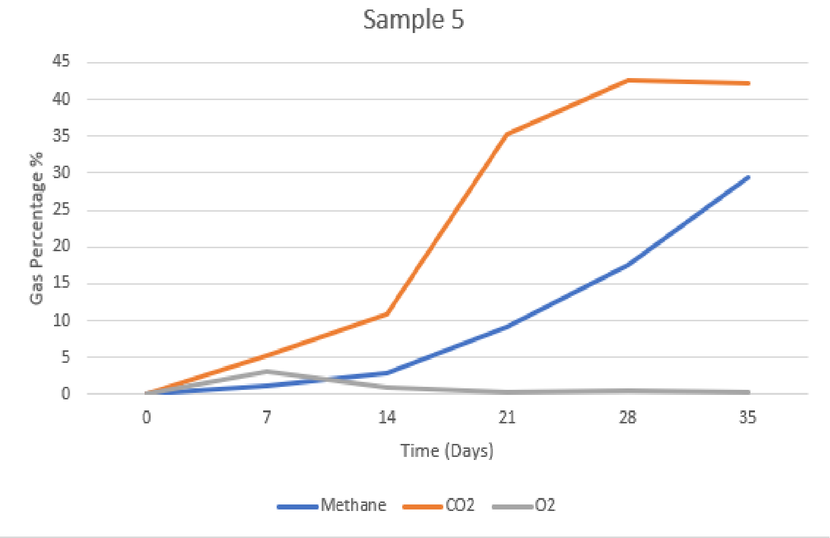


Figure 14: Reactor 5 gas analysis

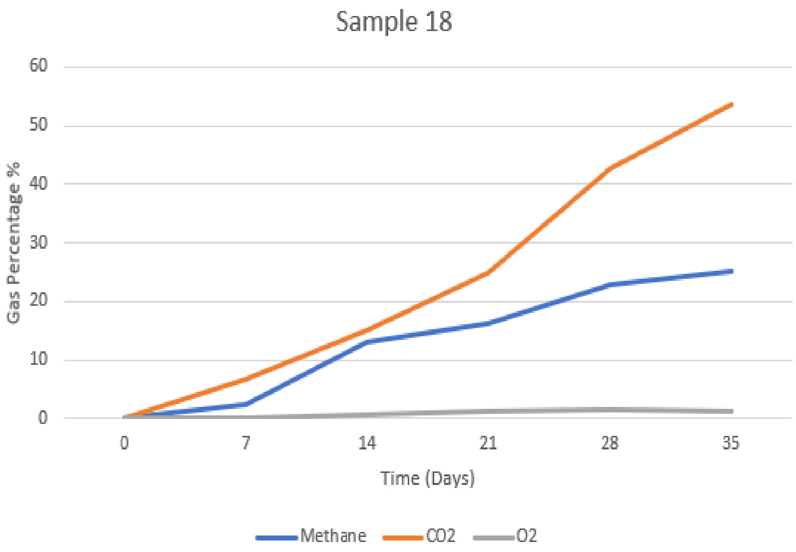


Figure 15: Reactor 18 gas analysis

2. Impact of low methane yield on pH:

In digesters with minimal methane production (0-6% yield), the pH remained around 6. This suggests that the organic matter wasn't being efficiently broken down by the microbes, which would normally produce acidic byproducts like organic acids.

3. Role of calcium carbonate ($CaCO_3$):

The use of $CaCO_3$ likely helped maintain a neutral pH level in the digesters. $CaCO_3$ acts as a buffer, neutralizing any acidic build-up produced during the anaerobic digestion process. This helps maintain a suitable environment for the methanogenic bacteria, although its effectiveness depends on the initial buffering capacity and the amount of acid produced.

4. Focus on Jackfruit Leaves

We investigated various leaves for methane production, but jackfruit leaves (reactors 5 and 18) stood out. Both samples contained 50 grams of jackfruit leaves, suggesting this might be the optimal amount for the experiment.

5. Visualizing Methane Yield

Methane yield from different jackfruit samples are shown in a single chart-

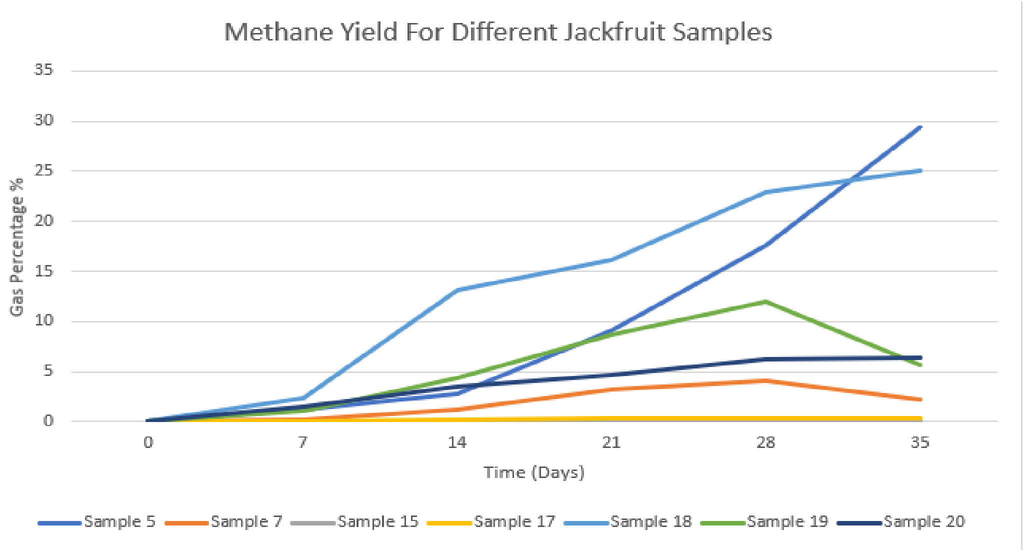


Figure 16: Methane yield for different reactors containing Jackfruit leaves

6. Possible factors of High Yield from Jackfruit Leaves

Several factors that likely contributed to the high methane yield from jackfruit leaves:

- **Carbohydrates and Cellulose:** These are complex sugars that microbes readily break down during a process called anaerobic digestion. This breakdown produces methane as a byproduct.
- **Optimal C/N Ratio:** Microbes need both carbon (C) for energy and nitrogen (N) for building proteins. The optimal C/N ratio ensures there's enough of both elements for efficient microbial growth and methane production.
- **Beneficial Bioactive Compounds:** Jackfruit leaves might contain unique compounds that stimulate the growth and activity of methane-producing microbes.
- **Low Lignin Content:** Lignin is a tough molecule that makes plant cell walls rigid. Low lignin content makes it easier for microbes to access and break down the jackfruit leaves, leading to higher methane production.

- **Easily Degradable Structure:** The physical structure of jackfruit leaves might be naturally more accessible to microbes compared to other materials, further enhancing methane production.

7. Reanalysis and Consistent Yield

Reactors 5 and 18 were retested at 60 days and showed a consistent 35% and 32% methane yield respectively. This suggests that jackfruit leaves have the potential for reliable methane production over time.

8. Thermal Pre-treatment Not Necessary

We further investigated whether pre-heating the leaves (thermal pre-treatment) would improve methane yield. However, the results suggest this additional step had no significant impact on methane production from leaves.

9. Minimal Hydrogen Sulfide (H_2S) Production

Hydrogen sulfide (H_2S) is an undesirable gas produced in some anaerobic digestion processes. The study reports H_2S generation was very low (less than 0.1 ppm) in all scenarios. This is a positive finding, as it indicates the process is well-controlled and produces minimal harmful byproducts.

10. Methane and CO_2 Trade-Off

As methane production increases, the percentage of CO_2 in the gas mixture decreases. This makes sense because both methane and CO_2 are products of the anaerobic digestion process, but microbes prioritize producing methane for energy. However, a certain amount of CO_2 is still necessary for optimal microbial growth.

11. Fresh Leaves and Zero Methane

We found that using freshly fallen green leaves in the digesters resulted in 0% methane production.

This could be due to several reasons:

- **Fresh leaves might have higher moisture content:** Excessive moisture can limit microbial activity and methane production.
- **Fresh leaves may contain compounds inhibiting methane-producing microbes:** Some plants have natural defense mechanisms that can hinder microbial growth. These compounds might be present in higher concentrations in fresh leaves.
- **Incomplete breakdown of fresh leaves:** The complex structures of fresh leaves might require longer breakdown times before microbes can efficiently produce methane.

Further investigation would be needed to pinpoint the exact reason behind zero methane yield from fresh leaves.

Our experiment's second phase was designed to increase the methane production's time efficiency. Nevertheless, the results we saw did not match our expectations, which prompted additional research and discussion.

Future research could look into possible ways to lessen the inhibitory effects seen in order to solve the constraints of our experiment. To improve the efficiency of methane production, for example, the pH levels, organic acid concentrations, and organic loading rates could be adjusted in order to enable microbial processes regain their balance.

Furthermore, a thorough examination of the metabolic pathways and microbial population dynamics involved in anaerobic digestion would yield important information for process improvement. Developing focused interventions to enhance methane production can be achievable by comprehending the intricate relationships and interdependencies among various microbes.

Chapter 5 Conclusion and Future Recommendation

5.1 Conclusion

5.1.1 Findings

To sum up, our research has shed important light on the variables affecting the formation of methane in anaerobic digestion processes. The main conclusions of our study provide insight into the influence of temperature, substrate choice, and pH on biogas output.

Firstly, our findings support the vital function pH plays in anaerobic digestion. The microbial activity and metabolic pathways involved in the synthesis of methane are greatly influenced by pH values. In order to maximize biogas output and foster circumstances that are suitable for methanogenic bacteria, it is imperative to maintain an ideal pH range.

Secondly, our research shows that different substrates produce different amounts of methane. This result highlights how crucial it is to choose anaerobic digestion substrates wisely in order to maximize biogas production. To maximize the process's overall efficiency, variables including the breakdown rates, nutritional content, and composition of the substrate should be taken into account.

Furthermore, maintaining a constant temperature significantly enhances methane production from fallen leaves during anaerobic digestion. A stable thermal environment optimizes the metabolic activity of the microorganisms responsible for breaking down the organic matter, leading to more efficient decomposition and biogas generation. Temperature fluctuations can disrupt microbial processes, reducing the rate of methane production. Typically, mesophilic conditions (around 35-40°C) are ideal, as they promote the growth of methanogenic bacteria, which are crucial for converting organic acids into methane. Consistent temperatures ensure a steady metabolic rate, maximizing methane yield and making the process more predictable and efficient.

Overall, our study contributes to the understanding of factors influencing methane production in anaerobic digestion and highlights the need for careful consideration of pH, substrate selection, and the effects of temperature. These findings have practical implications for the design and operation of biogas production systems, aiming to maximize methane yields and promote the development of sustainable energy generation.

5.2 Recommendations

Based on the findings of this study, further research and exploration are warranted to optimize the methane production process, increase methane yields, and reduce the methane generation time. The following recommendations outline potential avenues for future work:

Conduct experiments with varying sample sizes to understand their influence on methane production: Experimenting with different sample sizes of fallen leaves can provide insights into how the volume of feedstock affects methane yield. Larger sample sizes might simulate real-world conditions more accurately, but can also introduce complexities such as uneven microbial distribution and potential substrate inhibition. Small-scale experiments can be more controlled but might not reflect practical scalability. By systematically varying the sample sizes and monitoring methane production, researchers can determine the optimal feedstock quantity for maximum biogas yield and efficiency.

Research the effects of co-digestion using cafeteria waste alongside other feedstocks like dry mango and coconut leaves to improve methane yields and process efficiency: Co-digestion involves mixing multiple types of organic waste to create a more balanced nutrient profile, enhancing microbial activity and methane production. Cafeteria waste, which is rich in carbohydrates, proteins, and fats, can complement the lignocellulosic structure of dry mango and coconut leaves. This synergy can lead to improved biodegradability and higher methane yields. Research in this area would involve evaluating the optimal ratios of these feedstocks, understanding their synergistic effects, and analyzing the improvements in process efficiency and methane output.

Research about other pre-treatment methods such as chemical, biological, ultrasonic, etc.: Pre-treatment methods are crucial for breaking down the complex structure of lignocellulosic materials in fallen leaves, making them more accessible to anaerobic microbes. Chemical pre-treatments (e.g., acids, alkalis) can solubilize hemicellulose and lignin, biological methods (e.g., enzyme addition) can degrade cellulose, and ultrasonic pre-treatment can physically disrupt cell walls. Each method has its own advantages and drawbacks in terms of cost, efficiency, and environmental impact. Comparative research can identify the most effective pre-treatment strategy or combination thereof for maximizing methane production.

Investigate optimal dosage levels, application methods, and alternative additives such as Sodium bicarbonate ($NaHCO_3$), Sodium hydroxide (NaOH) to maximize biogas production: Additives like sodium bicarbonate and sodium hydroxide can help maintain optimal pH levels in the digester, promoting microbial activity and stability. Investigating the correct dosages and application methods involves determining how these additives interact with different feedstocks and microbial communities. Studies should focus on the balance between enhancing biogas production and preventing potential inhibitory effects due to excessive dosages. Optimal conditions should be identified to ensure maximum efficiency and biogas yield.

Perform comprehensive life cycle assessments to evaluate the environmental impacts of biogas production from feedstock cultivation to waste management: A life cycle assessment (LCA) considers the environmental impacts associated with all stages of biogas production, from feedstock cultivation and harvesting to biogas production, utilization, and waste management. By evaluating parameters such as greenhouse gas emissions, energy consumption, resource use, and potential ecological impacts, researchers can identify the most sustainable practices and mitigate adverse effects. This holistic approach ensures that biogas production contributes positively to environmental goals and informs policy and decision-making.

Carry out economic analysis to assess the financial viability of biogas production systems, guiding decision-making for sustainable and cost-effective energy solutions: Economic analyses involve evaluating the costs associated with biogas production, including feedstock procurement, pre-treatment, digestion, and post-treatment processes. By comparing these costs with the potential revenues from biogas and by-products (e.g., biofertilizers), researchers can determine the profitability of different biogas production systems. This analysis helps in identifying cost-saving opportunities, optimizing resource allocation, and providing a clear understanding of the financial feasibility, thereby guiding investments and policy-making for sustainable energy solutions.

Study elaborately why other tree leaves had low methane production and incorporate the study: Investigating why certain tree leaves produce less methane involves analyzing their chemical composition, structural characteristics, and the presence of inhibitory compounds. Factors such as high lignin content, low biodegradability, and unfavorable carbon-to-nitrogen ratios can hinder methane production. By understanding these factors, researchers can develop strategies to improve the digestibility of these leaves, such as tailored pre-treatment methods or co-digestion with more easily degradable substrates. This knowledge can expand the range of viable feedstocks for biogas production, enhancing overall efficiency and sustainability.

In conclusion, enhancing methane production from fallen leaves through anaerobic digestion involves a multifaceted approach, including optimizing sample sizes, exploring co-digestion with complementary feedstocks like cafeteria waste, and investigating various pre-treatment methods such as chemical, biological, and ultrasonic techniques. Additionally, the optimal use of additives like sodium bicarbonate and sodium hydroxide to maintain favorable conditions within the digester is crucial. Comprehensive life cycle assessments and economic analyses provide insights into the environmental and financial viability of biogas systems, while detailed studies on the low methane yields of certain tree leaves offer opportunities to expand and improve feedstock utilization. Collectively, these strategies contribute to more efficient, sustainable, and economically feasible biogas production from organic waste.

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