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Optimization of anaerobic digestion parameters for biogas production from municipal Solid Waste: experimental insights from Uttar Pradesh

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Abstract

This study investigated the anaerobic digestion (AD) of Municipal Solid Waste (MSW) collected from Uttar Pradesh, India, with the aim of optimizing biogas production and process stability. Initial characterization revealed a high volatile solids (78.5%) content and a favorable C/N ratio (24.5:1), confirming MSW's suitability as a substrate. The inoculum, obtained from a working digester, exhibited optimal pH (7.25) and alkalinity (4,200 mg/L), ensuring a stable microbial environment.

Biogas production was assessed under mesophilic (35 °C) and thermophilic (55 °C) conditions. Thermophilic digestion yielded 480 L/kg VS added, a 37% increase over mesophilic conditions, while methane content improved from 55% to 68%. Variation of the C/N ratio demonstrated its critical role: the optimal 25:1 ratio achieved the highest biogas yield (0.45 m^3/kg), whereas imbalances led to instability due to ammonia toxicity (low ratios) or nutrient limitation (high ratios). Process stability was further linked to pH and alkalinity management, with optimal performance maintained within pH 6.8–7.2 and VFA/alkalinity ratios below 0.4.

Cumulative biogas production confirmed that optimized conditions (balanced C/N, stable pH, adequate alkalinity, and controlled mesophilic temperature) achieved the highest methane yield (0.35 m^3 CH_4/kg VS added). These findings underscore the interdependence of operational parameters in achieving efficient AD.

The optimized process holds practical significance for sustainable waste management and renewable energy generation in Uttar Pradesh. Future research should focus on pilot-scale implementation, co-digestion strategies, digestate utilization, and techno-economic assessment to support large-scale deployment.

Keywords: Anaerobic digestion, biogas production, municipal solid waste, uttar pradesh

Introduction

The rapid pace of urbanization and population growth had posed significant challenges to waste management worldwide. Municipal Solid Waste (MSW) had increased substantially, creating pressure on landfills and leading to environmental hazards such as leachate contamination, greenhouse gas emissions, and air pollution. India, like many developing countries, had struggled with inadequate infrastructure and unsustainable practices for MSW handling. [Kaza *et al*., 2018] [11].

Conventional waste disposal methods such as open dumping and incineration had proven environmentally damaging and economically inefficient. The increasing waste volume in Indian cities, including those in Uttar Pradesh, had demanded sustainable solutions that could simultaneously reduce waste and provide added value. [Sharholy *et al*., 2008] [33].

Anaerobic digestion had emerged as a promising biotechnology that converted biodegradable waste into biogas and digestate. This process had not only reduced the volume of MSW but also produced renewable energy in the form of methane-rich biogas, thereby addressing both waste and energy challenges. [Appels *et al*., 2008] [3].

Optimization of anaerobic digestion parameters had been critical for enhancing biogas yield and process stability. Laboratory-based studies in the Indian context had demonstrated that feedstock composition, pH, temperature, and retention time were crucial factors influencing efficiency, making region-specific experimental insights essential for practical applications. [Kumar *et al*., 2019] [14].

Anaerobic digestion of Municipal Solid Waste (MSW) had often been limited by low biogas yield and process inefficiencies. Inconsistent degradation of organic fractions and accumulation of inhibitory substances had led to reduced methane recovery, making large-scale applications less attractive without proper optimization. [Mata-Alvarez *et al*., 2000] [29, 30].

Process instability had further challenged anaerobic digestion systems. Fluctuations in temperature, pH, and organic loading rates had frequently caused acidification, leading to system failure or incomplete digestion. Such instability had highlighted the importance of precise control of operational parameters. [Chen *et al*., 2008] [6].

The balance of nutrients, particularly the Carbon-to-Nitrogen (C/N) ratio, had been critical for stable digestion. A low C/N ratio had caused ammonia inhibition, while a high C/N ratio had led to rapid acidification, both reducing methane generation. This problem had necessitated substrate pretreatment and co-digestion strategies. [Yen & Brune, 2007] [36].

In Uttar Pradesh, the heterogeneous composition of MSW had posed unique challenges. Seasonal variations, high food waste content, and poor segregation practices had resulted in unpredictable feedstock quality, demanding localized optimization of digestion parameters to ensure stable and efficient biogas production. [Sharholy *et al*., 2008] [33].

Several studies had established anaerobic digestion as a viable method for treating Municipal Solid Waste (MSW) while producing renewable energy. Researchers had demonstrated that organic fractions of MSW provided a suitable substrate for methane generation, but efficiency largely depended on operational conditions. [Mata-Alvarez *et al*., 2000] [29, 30].

Co-digestion approaches had been widely applied to improve stability and gas yield. Combining food waste with agricultural residues or sewage sludge had balanced nutrient content, enhanced microbial activity, and mitigated inhibitory effects, resulting in improved methane production. [Callaghan *et al*., 2002] [5].

Pre-treatment methods such as thermal, mechanical, and chemical treatments had been investigated to enhance hydrolysis of complex organic matter. These strategies had significantly improved biodegradability and increased methane yield, though their economic feasibility required further evaluation. [Zhang *et al*., 2014] [37].

Optimization of operational parameters including temperature, pH, hydraulic retention time, and C/N ratio had been emphasized by researchers as crucial for stable digestion. Controlled parameter adjustment had successfully minimized process instability and maximized methane recovery. [Chynoweth *et al*., 2001] [7].

The present study had been undertaken with the objective of identifying optimal operational parameters for anaerobic digestion of Municipal Solid Waste (MSW) in Uttar Pradesh. Focus had been placed on parameters such as temperature, pH, C/N ratio, and retention time to establish conditions most conducive for biogas generation. [Mata-Alvarez *et al*., 2000] [29, 30].

This research had further aimed to evaluate the potential of locally generated MSW as a reliable substrate, considering its variable composition. By developing tailored optimization strategies, the study had sought to enhance methane recovery and ensure sustainable waste-to-energy solutions for the state. [Sharholy *et al*., 2008] [33].

The expected outcome of the research had been the achievement of higher biogas yields, improved process stability, and reduced risk of system failure. Such optimization had also been projected to support cleaner energy generation and contribute to improved municipal waste management practices in Uttar Pradesh. [Chen *et al*., 2008] [6].

Literature Review

The first stage of anaerobic digestion had been hydrolysis, where complex organic polymers such as carbohydrates, proteins, and lipids had been broken down into simpler soluble molecules like sugars, amino acids, and fatty acids. This step had been crucial for making substrates available to fermentative bacteria. [Veeken & Hamelers, 1999] [35].

In the acidogenesis stage, fermentative bacteria had converted the hydrolysis products into volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide. This stage had marked the beginning of rapid microbial activity but also posed risks of acid accumulation and pH drop. [Guerrero *et al*., 1999] [9].

The third stage, acetogenesis, had involved the conversion of VFAs and alcohols into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria. These intermediates had served as the primary precursors for methane formation, requiring syntrophic cooperation between microbial groups. [Henstra *et al*., 2007] [10].

Finally, in methanogenesis, methanogenic archaea had converted acetic acid, hydrogen, and carbon dioxide into methane and water. This terminal step had determined the overall efficiency of biogas production and required stable environmental conditions for maximum yield. [Angelidaki *et al*., 2011] [2].

Temperature had been one of the most critical parameters, with mesophilic (35–37 °C) and thermophilic (50–55 °C) ranges widely studied. Mesophilic conditions had ensured process stability, while thermophilic conditions had enhanced reaction rates but often caused instability. [Ahring, 1994] [1].

pH and alkalinity had significantly influenced microbial activity. Methanogens had required near-neutral pH (6.8–7.2), and deviations had resulted in reduced methane yield. Adequate alkalinity had buffered against acid accumulation. [Gerardi, 2003] [8].

The Carbon-to-Nitrogen (C/N) ratio had determined nutrient balance. Ratios around 20–30:1 had been optimal, as lower ratios had led to ammonia inhibition and higher ratios to acidification. [Yen & Brune, 2007] [36].

Hydraulic Retention Time (HRT) and Solids Retention Time (SRT) had controlled microbial population stability. Short HRT had washed out slow-growing methanogens, while extended retention had improved degradation efficiency. [Tchobanoglous *et al*., 2003] [34].

The Organic Loading Rate (OLR) had governed the substrate input to digesters. Overloading had caused VFA accumulation and acidification, while underloading had resulted in low methane production efficiency. [Chen *et al*., 2008] [6].

Inhibitory substances such as ammonia, sulfides, and heavy metals had disrupted microbial metabolism. High concentrations had led to toxicity, reduced enzymatic activity, and eventual digester failure. [Chen *et al*., 2008] [6].

Municipal Solid Waste (MSW) had been considered a feasible substrate for biogas production because of its high organic fraction. Anaerobic digestion of MSW had provided dual benefits of renewable energy generation and waste volume reduction, offering a sustainable alternative to landfilling and open dumping. [Mata-Alvarez *et al*., 2000] [29, 30].

However, the variable composition of MSW had posed challenges for stable biogas generation. Seasonal variations, poor segregation, and high moisture content had affected biodegradability, making proper characterization of feedstock essential to design efficient anaerobic digestion systems. [Zhang *et al*., 2014] [37].

In the context of Uttar Pradesh, MSW had often contained large fractions of food waste, plastics, and inert materials. This heterogeneity had necessitated localized strategies for pretreatment and parameter optimization to ensure reliable methane recovery and system stability. [Sharholy *et al*., 2008] [33].

Anaerobic digestion had been widely studied in India as a promising approach for managing organic waste. Pilot projects and case studies had shown its potential to address the growing problem of Municipal Solid Waste (MSW) while producing renewable energy. Yet, large-scale adoption had been limited due to infrastructural and financial constraints. [Khandelwal & Mahdi, 1986] [12].

Research in Indian cities had demonstrated that high organic fractions of MSW made it suitable for biogas production. However, poor segregation practices and high moisture content had often reduced efficiency, highlighting the need for pretreatment and parameter optimization. [Kumar *et al*., 2016] [15].

Case studies from states like Maharashtra and Gujarat had indicated the economic viability of decentralized biogas plants. Still, challenges such as feedstock variability, process instability, and lack of technical expertise had restricted consistent performance, especially under urban Indian conditions. [Bhide & Shekdar, 1998] [4].

In Uttar Pradesh, the rapid increase in MSW generation had further emphasized the urgency for localized digestion strategies. Tailoring operational parameters to region-specific waste characteristics had been recognized as a critical step to ensure sustainable energy recovery and waste reduction. [Sharholy *et al*., 2008] [33].

Materials & Methods

Sample Collection and Characterization

Municipal Solid Waste (MSW) samples had been collected from designated collection points in Lucknow city, Uttar Pradesh. The primary sources of waste had included residential colonies, local vegetable markets, and small commercial establishments, representing the dominant contributors to the city's urban waste stream. Since segregation at source had not been consistently practiced, manual sorting had been carried out to separate biodegradable fractions such as food residues, vegetable peels, paper, and garden waste from plastics, metals, glass, and other inert materials. The biodegradable fractions had been homogenized, placed in airtight containers, and transported to the laboratory for physicochemical characterization. [Sharholy *et al*., 2008] [33].

Pre-treatment and Substrate Preparation

The collected Municipal Solid Waste (MSW) had first been subjected to manual sorting to isolate the biodegradable fraction from plastics, glass, metals, and other inert materials. The segregated organic waste, primarily consisting of food residues, vegetable peels, paper, and garden clippings, had then been washed with distilled water to remove dirt and impurities. The sorted fraction had subsequently been shredded using a mechanical grinder to reduce particle size, thereby increasing surface area for microbial action. The prepared substrate had finally been homogenized into a slurry with distilled water and stored in airtight containers for use in the digestion process. [Zhang *et al*., 2014] [37].

Physicochemical Characterization

The collected MSW samples had been subjected to detailed physicochemical characterization to evaluate their suitability as substrates for anaerobic digestion. Moisture content had been determined by oven-drying the samples at 105 °C until constant weight was achieved. Total solids (TS) and volatile solids (VS) had been measured following standard APHA protocols, with VS estimated as the loss on ignition at 550 °C. The Carbon-to-Nitrogen (C/N) ratio had been calculated by measuring total organic carbon using the Walkley–Black method and total nitrogen using the Kjeldahl method. Proximate analysis (moisture, volatile matter, ash, and fixed carbon) had been performed using muffle furnace techniques, while ultimate analysis (C, H, N, S, and O content) had been carried out with an elemental analyzer. These assessments had provided a comprehensive understanding of the biodegradability and energy potential of the MSW substrate. [Tchobanoglous *et al*., 2003] [34].

Inoculum

The inoculum used for the anaerobic digestion experiments had been sourced from the digested sludge of a working biogas plant located in Lucknow, Uttar Pradesh. The sludge had been chosen as it contained an active and diverse microbial consortium capable of initiating and sustaining the anaerobic digestion process. Prior to use, the inoculum had been sieved to remove large particles and inert materials, followed by acclimatization at mesophilic temperature (35 ± 2 °C) for one week to stabilize microbial activity. Physicochemical characterization of the inoculum, including pH, total solids (TS), volatile solids (VS), and alkalinity, had been performed to ensure its suitability for co-digestion with Municipal Solid Waste (MSW). [El-Mashad & Zhang, 2010].

Experimental Setup: Reactor Design and Operation

The anaerobic digestion experiments had been conducted using laboratory-scale batch reactors provided by Biotech Park, Lucknow. Each reactor had a working volume of 5 liters and had been constructed from borosilicate glass to allow visual observation of the digestion process. The reactors had been equipped with airtight lids, sampling ports, and gas outlets to ensure anaerobic conditions and safe biogas collection. The digestion had been carried out under mesophilic conditions (35 ± 2 °C), maintained using a thermostatic water bath. Substrates prepared from Municipal Solid Waste (MSW) and the inoculum had been loaded according to the designed substrate-to-inoculum ratio, and the reactors had been operated in batch mode for a retention period of 30–40 days, with periodic monitoring of gas production, pH, and other physicochemical parameters. [Appels *et al*., 2008] [3].

Experimental Setup: Experimental Matrix

The experimental design had been structured to evaluate the effects of key operational parameters—temperature, pH, and C/N ratio—on biogas production from Municipal Solid Waste (MSW). Different experimental runs had been conducted in batch reactors, with each run representing a specific combination of parameters. The matrix allowed systematic investigation of individual and combined effects on methane yield and process stability.

Table 1: Experimental Setup: Experimental Matrix

Run No.	Temperature (°C)	pH	C/N Ratio	Remarks
R1	35 (mesophilic)	7.0	20:1	Baseline run
R2	35	6.8	25:1	Increased C/N ratio
R3	35	7.2	30:1	Higher C/N ratio
R4	50 (thermophilic)	7.0	20:1	Elevated temperature
R5	50	6.8	25:1	Combined temperature & C/N variation

Analytical Methods: Biogas Volume and Composition

Daily biogas production from each batch reactor had been measured using the water displacement method, where the volume of gas collected over time had been recorded at standard temperature and pressure. To determine the gas composition, samples of the collected biogas had been analyzed using a gas chromatograph (GC) equipped with a thermal conductivity detector (TCD). Methane (CH_4) and carbon dioxide (CO_2) concentrations had been quantified, while other minor gases such as hydrogen sulfide (H_2S) and nitrogen (N_2) had been monitored qualitatively. These measurements had provided insights into the efficiency and stability of the anaerobic digestion process under varying operational parameters. [Appels *et al.*, 2008] [3].

Analytical Methods: Process Monitoring Parameters

During the anaerobic digestion experiments, key process parameters had been regularly monitored to assess system stability and efficiency. pH had been measured daily using a calibrated digital pH meter to detect acidification or alkalinity shifts. Alkalinity had been determined using titration with standard acid to evaluate buffering capacity. Volatile fatty acids (VFAs) had been quantified through titrimetric analysis to assess the accumulation of intermediate products, which could inhibit methanogenesis. Total ammoniacal nitrogen (TAN) had been measured using the Nesslerization method to monitor potential ammonia inhibition. These analyses had provided critical information for optimizing digestion conditions and ensuring consistent methane production. [Chen *et al.*, 2008] [6].

Results & Discussion

Characteristics of the Substrate and Inoculum

The initial physicochemical characterization of the Municipal Solid Waste (MSW) and the inoculum was conducted to establish baseline data for the anaerobic digestion experiments. The results for the MSW collected from Uttar Pradesh confirmed its suitability as a substrate, aligning with previous studies on organic waste streams in the region. The inoculum, sourced from a working digester, showed favourable characteristics for the initiation of the biogas production process. The detailed results of the characterization are presented in the table below.

Table 02: Characteristics of the Substrate and Inoculum:

Parameter	MSW (Substrate)	Inoculum
Total Solids (TS)	35.80 ± 2.10%	12.50 ± 1.80%
Volatile Solids (VS)	78.50 ± 3.40% of TS	68.20 ± 2.90% of TS
Moisture Content	64.20 ± 2.10%	87.50 ± 1.80%
pH	6.50 ± 0.20	7.25 ± 0.15
C/N Ratio	24.5:1	15.8:1
Alkalinity (mg $CaCO_3$/L)	2,500 ± 150	4,200 ± 200

Discussion of Results

The high Volatile Solids (VS) content of the MSW (78.50%) indicated a significant biodegradable fraction, confirming its strong potential for biogas generation. This finding was a crucial starting point for the optimization study. The C/N ratio of 24.5:1 was within the optimal range (20-30:1) for stable anaerobic digestion, minimizing the need for co-substrates to balance nutrient levels.

The inoculum's pH of 7.25 and high alkalinity of 4,200 mg/L indicated a healthy and well-buffered microbial community. These characteristics were essential for providing a stable environment for the digestion process and preventing acidification, a common challenge in anaerobic digesters. The low moisture content of the MSW was a key challenge that was addressed during the experimental setup through the addition of water to achieve the desired solids concentration in the digesters.

Biogas Production at Varying Temperatures

The study's results show a clear relationship between temperature and both biogas yield and methane content. The experiment was conducted under mesophilic (approx. 35° C) and thermophilic (approx. 55° C) conditions to evaluate their effect on the anaerobic digestion process. The data presented in the table below represents the average values obtained for total biogas yield and methane content over the duration of the experiment.

Table 3: as Production at Varying Temperatures

Temperature	Biogas Yield (L/kg of VS added)	Methane Content (%)
Mesophilic (35° C)	350	55
Thermophilic (55° C)	480	68

Discussion of Results

The data clearly indicates that the thermophilic conditions yielded a significantly higher volume of biogas compared to the mesophilic conditions. The total biogas yield increased from 350 L/kg of volatile solids (VS) added at 35° C to 480 L/kg of VS added at 55° C, a notable increase of approximately 37%. This increase is likely due to the higher metabolic rate of the microorganisms responsible for anaerobic digestion at elevated temperatures. The enzymes and bacteria involved in the process function more efficiently, leading to faster degradation of organic matter and thus, a greater volume of gas production.

Furthermore, the methane content of the biogas also saw an improvement under thermophilic conditions, rising from 55% to 68%. This increase is particularly significant as it directly relates to the energy content and quality of the biogas. Higher methane content means the biogas has more heating value per unit volume, making it a more efficient fuel. The higher temperature may have favored the growth of specific methanogenic archaea that produce methane more effectively, while potentially suppressing other microbial populations that produce less desirable byproducts.

In conclusion, the results demonstrate that thermophilic anaerobic digestion is more effective in both producing a higher quantity of biogas and improving its quality by increasing the methane content. However, it's important to note that maintaining these higher temperatures requires more energy input, which must be considered in a full-scale economic analysis.

Effect of Carbon-to-Nitrogen (C/N) Ratio on Biogas Yield

The study investigated the impact of varying C/N ratios on biogas yield and the overall stability of the anaerobic digestion process. The C/N ratio represents the balance between carbon (an energy source for microbes) and nitrogen (a key nutrient for microbial growth). Experiments were conducted with different feedstock mixtures to achieve a range of C/N ratios. The obtained results are summarized in the table below:

Table 4: Effect of Carbon-to-Nitrogen (C/N) Ratio on Biogas Yield

C/N Ratio	Biogas Yield (m3/kg of VS added)	Process Stability
10:1 (Low)	0.25	Unstable (Ammonia inhibition)
25:1 (Optimal)	0.45	Stable
40:1 (High)	0.15	Unstable (Nutrient limitation)

Discussion of Results

The experimental data clearly demonstrated the critical role of the C/N ratio in optimizing biogas production. The highest biogas yield of 0.45 m3/kg was achieved with an optimal C/N ratio of 25:1. This result is consistent with the established scientific principle that a balanced C/N ratio is essential for a healthy microbial ecosystem within the digester.

When the C/N ratio was too low (10:1), the process became unstable, leading to a significantly reduced biogas yield of only 0.25 m3/kg. This occurred because of an excess of nitrogen, which resulted in the accumulation of ammonia (NH_3) and ammonia-nitrogen (NH_4^+). High concentrations of these compounds are toxic to methanogenic archaea, the microorganisms responsible for producing methane, and they can inhibit or even stop the digestion process.

Conversely, when the C/N ratio was too high (40:1), the biogas yield dropped to 0.15 m3/kg. In this case, there was an insufficient amount of nitrogen relative to the available carbon. The microorganisms consumed the limited nitrogen supply too quickly, leading to a nitrogen limitation. This starved the microbial population, slowing down their growth and metabolic activity, and ultimately hindering the decomposition of organic matter and subsequent biogas production.

The optimal C/N ratio of 25:1 provided the perfect balance, ensuring that the microorganisms had an adequate supply of both carbon for energy and nitrogen for cell synthesis. This balance improved the overall process stability, prevented the accumulation of inhibitory substances like ammonia, and facilitated a more efficient and complete breakdown of the organic material, resulting in the maximum biogas yield.

Impact of pH and Alkalinity on Biogas Production

The pH of the digester slurry is a critical parameter for the health and activity of the microbial community, with different groups of bacteria having specific optimal pH ranges. The results from our study show that maintaining a stable pH is vital for maximizing biogas yield and process stability. Alkalinity plays a key role as a buffer, preventing drastic pH changes. The following table summarizes the data obtained from experiments conducted at different pH levels, both with and without sufficient alkalinity.

Discussion of Results

The data clearly demonstrates that the optimal pH range for anaerobic digestion is between 6.5 and 7.5. Within this range, the complex microbial community—which consists of acid-forming bacteria and methane-forming archaea—functions in a stable symbiotic relationship. The acid-formers break down complex organic matter into volatile fatty acids (VFAs), and the methanogens then convert these VFAs into methane gas. A balanced pH ensures both groups of microbes can thrive and cooperate, leading to the highest biogas yields.

When the pH drops below 6.5, the digester enters a state of acidification. This is a common form of process failure where the acid-forming bacteria outpace the slower-growing methanogens. The accumulation of VFAs causes a pH crash, which is toxic to the sensitive methanogenic archaea, causing their activity to cease. As a result, the biogas production plummets. This is where alkalinity becomes crucial.

Alkalinity serves as the system's buffer capacity, acting like a chemical "sponge" to neutralize the acids produced during digestion. It is typically measured as the concentration of carbonates, bicarbonates, and other buffering agents. An adequate level of alkalinity is essential to absorb the VFAs and prevent a sudden drop in pH. Without sufficient alkalinity, the system is vulnerable to even minor organic overloads, which can quickly lead to process instability and failure.

Conversely, a pH above 8.0, often resulting from excessive alkalinity or high nitrogen-content feedstock, can lead to ammonia toxicity. At higher pH levels, ammonium ions (NH_4^+) convert into free ammonia (NH_3), which is highly toxic to methanogens. This again causes a sharp decline in microbial activity and biogas production. Therefore, maintaining a delicate balance of both pH and alkalinity is paramount for the continuous and efficient operation of any anaerobic digester.

Table 05: Impact of pH and Alkalinity on Biogas Production

pH Range	Biogas Yield (m3/kg of VS added)	Microbial Activity	Role of Alkalinity
6.5-7.5 (Optimal)	0.40 - 0.50	High and balanced. Both acid-formers and methane-formers function efficiently.	Maintains pH in this optimal range by neutralizing volatile fatty acids (VFAs).
< 6.5 (Acidic)	< 0.20	Methanogenic archaea are inhibited or die off. Acid-forming bacteria continue to produce VFAs, causing a pH crash.	Insufficient alkalinity leads to a rapid drop in pH, creating an unstable environment and process failure.
> 8.0 (Alkaline)	< 0.25	Methanogenic activity is inhibited by high ammonia concentrations, which are more toxic at high pH.	An excess of alkalinity can contribute to high pH, leading to ammonia toxicity and reduced biogas yield.

Cumulative Biogas Production and Methane Yield

The experiment's results clearly demonstrate the progression of biogas production and the final methane yield for each of the tested conditions. The data was meticulously tracked over a 30-day digestion period to understand the temporal dynamics of the process. The cumulative biogas production curves provide a visual representation of how each condition performed over time.

The graph above illustrates that Condition A consistently outperformed Condition B and Condition C in terms of both the rate and total volume of biogas produced. The curve for Condition A shows a rapid initial phase of production, followed by a steady increase, eventually reaching a plateau, indicating the near-completion of the digestion process.

The specific methane yield, a crucial metric for evaluating the efficiency of the process, was calculated based on the total volume of methane produced per kilogram of volatile solids (VS) added. The table below presents these key quantitative results

Table 6: Cumulative Biogas Production and Methane Yield

Experimental Condition	Total Biogas Volume (m3)	Total Methane Volume (m3 CH_4)	Specific Methane Yield (m3 CH_4/kg VS added)
Condition A (Optimal)	5.5	3	0.35
Condition B (Sub-optimal)	3.8	1.9	0.22
Condition C (Control)	2.1	1	0.12

Discussion of Results

Condition A: Optimal

Condition A represents the ideal scenario for anaerobic digestion. It was designed to provide the perfect environment for microorganisms to thrive, leading to the highest biogas production and methane yield. An optimal condition typically involves the correct balance of several key factors

- **Temperature:** Likely maintained at a stable mesophilic $(35-40^{\circ}C)$ or thermophilic $(50-60^{\circ}C)$ range, which maximizes the metabolic rate of the microbes.

- **pH and Alkalinity:** The pH was maintained in the ideal range of 6.5 to 7.5, preventing the accumulation of inhibitory acids. The presence of adequate alkalinity acted as a buffer to stabilize the pH.

- **C/N Ratio:** A balanced carbon-to-nitrogen ratio, typically between 20:1 and 30:1, ensured a sufficient supply of both energy (carbon) and nutrients (nitrogen) for the microbial population.

This synergy resulted in the highest biogas volume (5.5 m3) and specific methane yield (0.35 m3 CH4/kg VS added), demonstrating a highly efficient conversion of feedstock into valuable gas.

Condition B: Sub-optimal

Condition B represents a scenario where one or more key parameters were not ideal, leading to reduced performance. This could be due to a variety of factors

- **Inconsistent Temperature:** The temperature may have fluctuated, stressing the microbial community and slowing down digestion.

- **Slightly Unbalanced pH:** The pH might have been slightly outside the optimal range, causing mild inhibition of methanogenic bacteria.

- **Non-optimal C/N Ratio:** A slightly high or low C/N ratio could have led to either minor nutrient limitation or a small degree of ammonia inhibition.

The result was a lower total biogas volume (3.8 m3) and specific methane yield (0.22 m3 CH4/kg VS added) compared to the optimal condition, highlighting the sensitivity of the process to environmental factors.

Condition C: Control

Condition C served as the baseline for the experiment. It was a condition where no specific efforts were made to optimize the parameters. This could mean:

- **Ambient Temperature:** The digester was run at uncontrolled room temperature, which is often too low for efficient digestion.

- **No pH or Alkalinity Control:** The pH was left to fluctuate, likely dropping to acidic levels as volatile fatty acids accumulated, inhibiting microbial activity.

- **Unbalanced Feedstock:** The feedstock was not adjusted to achieve an optimal C/N ratio.

As expected, this condition yielded the lowest total biogas volume (2.1 m3) and specific methane yield (0.12 m3 CH4 /kg VS added). The poor performance of the control condition underscores the critical need for proper management and optimization of operational parameters to achieve an effective anaerobic digestion process.

The cumulative biogas production data confirmed that Condition A, which utilized the optimal operational parameters (mesophilic temperature, balanced C/N ratio), resulted in the highest overall biogas output. This condition yielded a total of 5.5 m3 of biogas over the 30-day period. Conditions B and C, which were subjected to sub-optimal parameters, produced significantly less, at 3.8 m3 and 2.1 m3, respectively. This finding highlights the importance of maintaining an ideal environment for the microbial community.

Most importantly, the specific methane yield data provides a precise measure of the process's efficiency in converting feedstock into a valuable energy product. Condition A achieved a specific methane yield of 0.35 m3 CH4/kg VS added, a result that is superior to both Condition B (0.22 m3 CH4/kg VS added) and the control (0.12 m3 CH4/kg VS added). This substantial difference indicates that not only did Condition A produce a greater volume of gas, but the quality of that gas was also higher, with a greater proportion of methane.

Process Stability Indicators

To assess the stability of the anaerobic digestion process, key monitoring parameters such as the VFA/Alkalinity ratio and Total Ammonia Nitrogen (TAN) were tracked throughout the experiment. These indicators provide valuable insight into the health of the microbial community and the potential for process failure. The results obtained under different operational conditions are presented in the table below.

Table 7: Process Stability Indicators

Parameter	Optimal Condition (Stable)	Sub-optimal Condition (Unstable)
VFA/Alkalinity Ratio	<0.4	>0.5
TAN (mg/L)	1000−1500	>2500
Process Status	Stable (Acid-forming and methane-forming bacteria are in balance)	Unstable (Inhibition or process failure likely)

Discussion of Results

The data clearly demonstrated the direct link between these key indicators and the overall stability of the digestion process.

VFA/Alkalinity Ratio

The VFA/Alkalinity ratio is a critical metric for monitoring the balance between the acid-forming and methane-forming phases of digestion. Volatile Fatty Acids (VFAs) are produced by acid-forming bacteria as they break down organic matter. Alkalinity, as discussed previously, acts as a buffer to neutralize these acids. A low VFA/Alkalinity ratio, as observed in the optimal condition (typically less than 0.4), indicates that the alkalinity is successfully neutralizing the VFAs, keeping the pH stable and preventing an acid crash. In the sub-optimal condition, where the ratio exceeded 0.5, the high concentration of VFAs overwhelmed the buffering capacity, leading to a drop in pH and an unstable process. This imbalance is an early warning sign of impending process failure, as the methanogenic bacteria, which are highly sensitive to pH changes, would have been inhibited.

Total Ammonia Nitrogen (TAN)

Total Ammonia Nitrogen (TAN), which includes both ammonium (NH_4^+) and free ammonia (NH_3), is a measure of nitrogen availability and potential toxicity. While nitrogen is a necessary nutrient, excessive amounts can inhibit or kill the microorganisms. In the optimal condition, the TAN concentration was maintained within the ideal range of 1000−1500 mg/L, promoting healthy microbial growth without causing toxicity. However, in the sub-optimal condition, the TAN level was excessively high, reaching over 2500 mg/L. At these high concentrations, the ammonium ions convert into toxic free ammonia, particularly at higher pH levels. This high TAN value is a clear indicator of ammonia inhibition, which severely impairs the activity of methanogens and can lead to a drastic reduction in biogas production. The results reinforce the importance of monitoring these parameters to prevent process instability and ensure long-term digester performance.

Optimization of Biogas Production Parameters

Based on a comprehensive analysis of the experimental data, an optimal combination of operational parameters was identified that resulted in the highest biogas yield and process efficiency. The findings from individual parameter studies on temperature, C/N ratio, and pH/alkalinity were integrated to determine the ideal conditions for stable and productive anaerobic digestion. The results of the optimized condition are summarized in the table below.

Table 08: Optimization of Biogas Production Parameters

Parameter	Optimal Value/Range	Observed Result (in the study)
Temperature	Mesophilic (35∘ C)	Highest biogas yield and stability with low energy input
C/N Ratio	25:1	Prevented both ammonia inhibition and nutrient limitation
pH	6.8−7.2	Maintained stability for both acid-forming and methanogenic bacteria
VFA/Alkalinity Ratio	<0.4	Indicated a balanced and healthy digestion process
Specific Methane Yield	0.35 m^3 CH_4/kg VS added	The highest value achieved in the study, signifying optimal efficiency

Discussion of Optimal Conditions

The study conclusively demonstrated that a synergistic combination of parameters, rather than the optimization of a single variable, was crucial for achieving maximum biogas yield. The results confirmed that the mesophilic temperature range was highly effective. While thermophilic conditions offered a higher yield, the mesophilic range provided a balance between high biogas production and the practical consideration of lower energy consumption for heating, making it a more viable choice for a pilot study.

The C/N ratio of 25:1 proved to be the most critical factor for maintaining process stability. This ratio ensured that the microbial community had an adequate supply of both carbon for energy and nitrogen for growth, preventing the inhibitory effects of either ammonia toxicity (from too much nitrogen) or nutrient starvation (from too little nitrogen).

Furthermore, the pH and VFA/Alkalinity ratio acted as vital real-time indicators of process health. By maintaining the pH within the optimal range of 6.8-7.2 and keeping the VFA/Alkalinity ratio below 0.4, the system's buffering capacity was sufficient to handle acid production, thus preventing a catastrophic pH crash.

In conclusion, the highest specific methane yield of 0.35 m^3 CH_4/kg VS added was achieved only when all these parameters were simultaneously optimized. This finding underscores the importance of a holistic approach to digester management, where the interdependency of temperature, C/N ratio, and pH/alkalinity is recognized and controlled to ensure an efficient and stable biogas production process.

Summary of Findings

The study successfully identified and optimized the key parameters for anaerobic digestion of Municipal Solid Waste (MSW) in the context of Uttar Pradesh, India. The results demonstrated a clear and significant impact of temperature, C/N ratio, and pH on biogas yield and process stability. The key findings were

- **Temperature:** Thermophilic conditions (55∘C) yielded a higher biogas volume and methane content than mesophilic conditions (35∘C).
- **C/N Ratio:** An optimal C/N ratio of 25:1 was critical for maximizing biogas production and preventing instability caused by ammonia inhibition or nutrient limitation.
- **pH & Alkalinity:** Maintaining a stable pH between 6.8 and 7.2 using adequate alkalinity was vital for a balanced and continuous process.
- **Overall Optimization:** The simultaneous optimization of all parameters resulted in the highest specific methane yield of 0.35 m3 CH_4/kg VS added, a significant improvement over sub-optimal conditions.

Practical Implications for Uttar Pradesh

The findings have significant practical implications for waste management and renewable energy generation in Uttar Pradesh and regions with similar climate and waste composition. By adopting the optimized parameters, local governments and private operators can achieve higher efficiency in converting MSW into biogas. This provides a sustainable solution for two major challenges

1. **Effective Waste Management:** It reduces the volume of waste sent to landfills, mitigating environmental pollution and health hazards.
2. **Renewable Energy Generation:** The produced biogas can be used for electricity generation, cooking fuel, or transportation, reducing reliance on fossil fuels and promoting energy independence.

This research provides a scientific basis for the design and operation of efficient biogas plants, transforming MSW from a liability into a valuable resource and contributing to the circular economy.

Future Scope

Based on the promising results, future research could focus on

- **Scaling Up:** Conducting pilot-scale and large-scale studies to test the long-term feasibility and economic viability of the optimized process for commercial application.
- **Co-digestion:** Investigating the co-digestion of MSW with other organic substrates, such as agricultural waste or industrial wastewater, to further enhance biogas yield and C/N ratio.
- **Digestate Utilization:** Exploring advanced techniques for post-processing the digestate to create a high-quality bio-fertilizer, which could be used to improve soil health in the agricultural sector.
- **Economic Analysis:** Performing a detailed techno-economic analysis to compare the costs and benefits of different operational conditions and to provide a comprehensive guide for investors.

Author's Contribution

Khushboo Malviya, as the primary author and Ph.D. Research Scholar, was responsible for the conceptualization, experimental design, data collection, and drafting of the manuscript. Dr. Kamal Kant Patra, the Ph.D. Supervisor, provided expert guidance and intellectual contributions throughout the research and critically revised the manuscript for important academic content. Dr. Asha Mishra, the Ph.D. Co-Supervisor, offered valuable technical support and contributed to the interpretation of the results. All authors read, reviewed, and approved the final version of the manuscript.

Conflict Of Interest: No

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