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Organic Waste to Energy: Enhancing Biodigester Efficiency in Oman for Sustainable Development

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PUBLISHED BY**ABSTRACT**

Organic waste presents a significant environmental and economic opportunity for renewable energy generation through anaerobic digestion. This study investigates the optimization of biodigester systems tailored to Oman's unique climatic conditions and waste characteristics. Using a mixed-methods approach that integrates experimental data from 30-day monitoring with simulated scenarios, the study evaluates five feedstock types, namely food waste, agricultural residues, livestock manure, mixed organic waste, and food and crop waste, together with three pretreatment methods: mechanical, thermal, and chemical. The findings demonstrate that thermal pretreatment enhances biogas yield by up to 25–30%, while food waste and food and crop waste achieve the highest methane contents of 65% and 64%, respectively. Modeled environmental and economic analyses indicate potential benefits, including up to a 70% reduction in greenhouse gas emissions, a 90% waste diversion rate, payback periods of 2–2.5 years for high-yield feedstocks, and net economic returns exceeding 30%. Simulated data further highlight the potential of co-digestion, system adaptations for arid climates, and real-time monitoring technologies to enhance biodigester performance. The study aligns with Oman Vision 2040 by providing practical insights into sustainable waste management and renewable energy integration. By addressing technical, environmental, and economic dimensions, this research offers a scalable and replicable model for advancing biodigester systems in Oman.

1. INTRODUCTION

The global shift toward sustainable energy solutions has underscored the critical need to address the challenges associated with organic waste management. Organic waste, often perceived as a burden, represents an untapped resource for renewable energy generation through anaerobic digestion (Yang et al. 2024). This process not only mitigates environmental pollution but also contributes to the circular economy by converting organic waste into valuable by-products such as biogas and nutrient-rich digestate (Piadeh et al. 2024). However, optimizing the efficiency of biodigesters remains a key challenge, particularly in regions such as Oman, where unique climatic conditions and waste characteristics require tailored solutions.

In Oman, rapid urbanization, population growth, and increased agricultural activities have led to a surge in organic waste generation. Despite this, traditional waste disposal methods such as landfilling dominate, resulting in greenhouse gas emissions, resource wastage, and environmental degradation (Akhlar et al. 2020). Aligning with Oman Vision 2040 sustainability goals, there is a pressing need to adopt innovative technologies (Ahmad and Wu 2022) that transform

organic waste into energy while minimizing ecological footprints.

This study focuses on enhancing the efficiency of biodigesters by leveraging advanced techniques in feedstock optimization, pretreatment, and system design (Al-Huqail et al. 2022), tailored to the arid climate and waste characteristics of Oman. By integrating a two-stage biodigestion process comprising hydrolysis and methanogenesis, the study aims to maximize biogas yield while ensuring the sustainable management of organic waste (AlQattan et al. 2018). In addition, the valorization of digestate as a nutrient-rich fertilizer supports the country's agricultural development objectives, thereby promoting both environmental and economic benefits (Ampese et al. 2022).

The outcomes of this research have the potential to revolutionize organic waste-to-energy systems in Oman by offering a scalable and efficient model that supports energy security, environmental sustainability, and waste management (Amuzu-Sefordzi et al. 2018). By addressing the challenges of biodigester optimization, this study contributes to the global discourse on sustainable development and provides actionable insights for policymakers and industry stakeholders.

2. BACKGROUND AND CONTEXT

2.1. Global Challenges in Organic Waste Management

The rapid growth of urban populations and economic activities has significantly increased organic waste generation worldwide. According to the United Nations Environment Programme, over 1.3 billion tons of food waste are generated annually, with an estimated 60% classified as organic (Ayodele et al. 2017). The mismanagement of organic waste poses significant environmental and public health risks, including methane emissions, groundwater contamination, and inefficient resource utilization (Ayodele et al. 2018). Traditional disposal methods, such as landfilling and open dumping, further exacerbate these issues by contributing to greenhouse gas emissions and occupying valuable land resources (Barbera et al. 2022).

While technological solutions such as composting and anaerobic digestion have emerged, several challenges persist. The heterogeneity of organic waste, lack of efficient collection systems, and insufficient policy support often hinder large-scale adoption of sustainable waste management practices (Shaibur et al. 2021). Furthermore, the integration of advanced technologies, such as biodigesters, is frequently impeded by high initial investment costs, operational inefficiencies, and public resistance (Einarsson & Persson 2017) due to limited awareness of the benefits.

2.2. Organic Waste in Oman: Current Practices and Challenges

In Oman, the management of organic waste has become a pressing issue due to rapid urbanization, population growth, and a thriving agricultural sector. Organic waste constitutes a significant portion of municipal solid waste, with food waste, agricultural residues, and livestock manure forming the bulk of this category (Falahi and Avami 2020). However, traditional practices such as landfilling dominate, with over 60% of organic waste disposed of in dumpsites, leading to environmental degradation and resource loss (Francini et al. 2019).

The hot and arid climate in Oman presents unique challenges for organic waste management, as high temperatures accelerate the decomposition process, creating odor and leachate issues (Gao et al. 2021). Additionally, the absence of segregated waste collection systems limits the recovery of organic waste for value-added processes (Bywater et al. 2022). Despite these challenges, Oman holds significant potential for leveraging organic waste as a resource (Oman Environmental Services Holding Company 2023). The country's abundant agricultural residues and growing focus on renewable energy provide opportunities to transition from linear waste disposal methods to circular economy practices (Chen et al. 2023).

Logistical feasibility is a critical consideration for implementing biodigester systems in Oman. Decentralized collection of diverse feedstocks from urban, agricultural, and livestock sources poses challenges such as transport costs, infrastructure limitations, and the need for coordinated collection schedules. Additionally, certain waste streams exhibit seasonal variability; for example, agricultural residues are typically abundant post-harvest but scarce during off-seasons. This variability can impact the consistency of feedstock supply, requiring planning for storage, blending, or alternative sourcing strategies to maintain stable biodigester operation year-round.

2.3. Relevance to Oman Vision 2040

Oman Vision 2040 outlines a comprehensive framework for achieving sustainable development by emphasizing economic diversification, environmental stewardship, and energy security. Central to this vision is the promotion of renewable energy and sustainable waste management practices (Massaro et al. 2015). Transforming organic waste into energy aligns with these priorities by addressing key environmental challenges while contributing to the nation's renewable energy targets (Zhou et al. 2022).

Biodigesters, as a technology for organic waste valorization, provide a dual benefit for Oman: mitigating the

environmental impact of waste and generating biogas as a renewable energy source (Yong et al. 2021). Additionally, the by-product of anaerobic digestion, digestate, can serve as an organic fertilizer, supporting sustainable agricultural practices and reducing dependence on chemical inputs (Yalcinkaya 2020). By adopting innovative strategies to optimize biodigester efficiency, Oman can not only achieve its waste management goals but also position itself as a regional leader in sustainable development practices.

This research aims to address these pressing issues by exploring optimized biodigester designs and strategies tailored to Oman's unique conditions, contributing directly to the achievement of Vision 2040 objectives.

3. BIODIGESTER TECHNOLOGY: AN OVERVIEW

3.1. Principles of Anaerobic Digestion

Anaerobic digestion (AD) is a biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas (a mixture primarily of methane and carbon dioxide) and digestate, a nutrient-rich by-product (Yadav et al. 2022). This process occurs in four sequential stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

- Hydrolysis involves breaking down complex organic materials, such as carbohydrates, proteins, and fats, into simpler soluble compounds, including sugars, amino acids, and fatty acids.
- Acidogenesis converts these simpler compounds into volatile fatty acids, hydrogen, and carbon dioxide.
- Acetogenesis further breaks down volatile fatty acids into acetic acid, along with additional hydrogen and carbon dioxide.
- Methanogenesis is the final stage, during which methanogenic microorganisms convert acetic acid and hydrogen into methane, the primary energy carrier in biogas.

AD offers several benefits, including the sustainable management of organic waste, the reduction of greenhouse gas emissions, and the production of renewable energy (Welfle & Röder 2022). However, optimizing this process requires precise control of parameters such as temperature, pH, and retention time to maximize biogas yield and system efficiency (Walker et al. 2017).

3.2. Two-Stage Biodigester Systems: Hydrolysis and Methanogenesis

Two-stage biodigester systems separate the hydrolysis and methanogenesis stages into distinct reactors, allowing for better control of the conditions in each phase (Vaneeckhaute

et al. 2018). This separation addresses one of the major challenges in single-stage digesters: the incompatibility of the optimal conditions required by hydrolytic and methanogenic microorganisms (Carrere et al. 2016).

3.2.1. Stage 1: Hydrolysis Reactor

In the first stage, organic matter undergoes hydrolysis and acidogenesis. This reactor operates under conditions that favor the breakdown of complex molecules into simpler compounds, such as a slightly acidic pH and shorter retention times (Zheng & Li 2024). By isolating this phase, process efficiency is improved, and the risk of system instability is reduced.

3.2.2. Stage 2: Methanogenesis Reactor

The second stage focuses on methanogenesis, during which the products from the first stage are converted into methane and carbon dioxide. This reactor typically requires a neutral pH and a longer retention time to support methanogenic microorganisms (Pham Van et al. 2020). This separation allows for better control of methanogenesis and prevents acidification, a common issue in single-stage systems.

Two-stage systems are particularly advantageous for processing heterogeneous or high-solid-content feedstocks, which are common in organic waste streams (Ruiz-Aguilar et al. 2022). The improved stability, higher biogas yield, and reduced risk of process failure make them an attractive option for optimizing biodigester performance (Nkemka et al. 2014), particularly in challenging climates such as that of Oman.

3.3. Advances in Biodigester Design and Efficiency

Recent advancements in biodigester technology have focused on improving efficiency, scalability, and adaptability to diverse environmental conditions and waste types (Piadeh et al. 2024). Key innovations include:

1. **Enhanced Pretreatment Technologies:** Techniques such as thermal, chemical, and mechanical pretreatment improve the digestibility of feedstocks, accelerate the hydrolysis process, and increase biogas yield (Issahaku et al. 2024).
2. **Integrated Monitoring and Control Systems:** IoT-based sensors and real-time monitoring systems have transformed biodigester operations. These systems provide continuous data on parameters such as temperature, pH, and gas production, enabling precise adjustments to optimize performance (de Souza Guimarães & da Silva Maia 2023).
3. **Hybrid Digesters:** Hybrid designs combine features of multiple reactor types, such as continuous stirred-tank reactors (CSTRs) and plug-flow reactors, to

- improve feedstock flexibility and gas production efficiency.
- 4. Energy Recovery and Heat Integration:** Waste heat from biogas combustion can be recycled to maintain reactor temperatures, particularly in colder environments, thereby reducing operational costs (Keerthana Devi et al. 2022).
 - 5. Modular and Scalable Designs:** Modular systems allow for incremental capacity expansion, making biodigesters accessible to a wider range of users, from small-scale farmers to large industrial facilities (Josimović et al. 2024).
 - 6. High-Solids Anaerobic Digestion (HSAD):** HSAD systems are designed for feedstocks with high solids content, minimizing water usage, which is a critical advantage in arid regions such as Oman.

By leveraging these advancements, biodigesters can achieve higher energy conversion efficiency and enhanced operational stability, making them a cornerstone of sustainable organic waste management (Obileke et al. 2020). In the context of Oman, these technologies can be tailored to local conditions, addressing specific challenges such as high ambient temperatures and diverse waste compositions.

4. MATERIALS AND METHODS

4.1. Feedstock Analysis and Selection

The selection of feedstock is a critical step in optimizing the biodigester process, as the biochemical properties of the input materials significantly influence biogas yield and system performance. Organic waste samples, including food waste,

agricultural residues, and livestock manure (Gitinavard et al. 2020), were collected from various urban, rural, and agricultural sources across Oman (Table 1).

- Chemical Analysis:** The samples were analyzed (Table 2) for key parameters such as moisture content, volatile solids (VS), total solids (TS), pH, and carbon-to-nitrogen (C/N) ratio using standard protocols (e.g., APHA guidelines).
- Suitability Assessment:** A comparative analysis (Table 2) of different feedstocks was conducted to evaluate their potential for co-digestion. Feedstocks with complementary properties, such as high nitrogen content paired with high carbon residues, were identified to achieve an optimal C/N ratio of 20–30, ensuring maximum microbial activity and biogas production (Dubois et al. 2019).

Table 2 summarizes key parameters like moisture content, volatile solids, total solids, pH, and C/N ratio for different feedstocks. It highlights how these properties influence their suitability for anaerobic digestion and co-digestion. For example, food waste, with high moisture and volatile solids, is readily digestible but needs pairing with high-carbon residues like agricultural waste due to its low C/N ratio (Ippolito et al. 2020). Conversely, agricultural residues, with a high C/N ratio, complement nitrogen-rich feedstocks like livestock manure. Mixed organic waste and food and crop waste exhibit balanced properties, making them highly suitable for co-digestion without major adjustments (Prussi et al. 2022). This table effectively links chemical properties to practical applications, ensuring feedstock combinations are optimized for maximum biogas production and stable biodigester performance.

Table 1: Sample collection locations and details for organic waste analysis.

Location	Sample Type	Source	Latitude	Longitude	Sample Volume (kg)
Muscat	Food Waste	Urban Households	23.588	58.3829	50
Salalah	Agricultural Residues	Agricultural Farms	17.0198	54.089	60
Sohar	Livestock Manure	Livestock Farms	24.3643	56.7075	55
Nizwa	Mixed Organic Waste	Urban and Rural Collection	22.9333	57.5333	70
Sur	Food and Crop Waste	Urban Markets and Farms	22.5667	59.5289	65

Table 2: Chemical properties and co-digestion suitability of feedstock.

Feedstock Type	Moisture Content (%)	Volatile Solids (VS %)	Total Solids (TS %)	pH	C/N Ratio	Suitability for Co-Digestion
Food Waste	75	85	25	5.5	18	High (Pair with high-C residues)
Agricultural Residues	20	60	80	6.8	40	High (Pair with high-N residues)
Livestock Manure	65	55	35	7.2	15	Medium (Complementary with crop waste)
Mixed Organic Waste	60	65	40	6	25	High (Balanced composition)
Food and Crop Waste	50	70	30	6.5	22	High (Ready for co-digestion)

4.2. Pretreatment Techniques for Organic Waste

To enhance the biodegradability of feedstocks and improve biogas yield, pretreatment techniques were employed (George et al. 2021). The pretreatment methods (Table 3) were selected based on the specific composition of the organic waste and the operational constraints of the biodigester.

4.2.1. Mechanical Pretreatment

Waste was shredded to reduce particle size, thereby increasing the surface area available for microbial activity during hydrolysis.

4.2.2. Thermal Pretreatment

Samples were subjected to controlled heating at 70°C for 1 h to break down complex organic compounds, enhance solubility, and eliminate pathogens.

Thermal pretreatment at 70°C for 1 h was selected based on its proven ability to break down complex organic structures, increase solubility, and reduce pathogens in organic waste streams. Prior studies have demonstrated that this temperature range (60–80°C) effectively enhances substrate biodegradability and improves biogas yield by 20–35% (Amin et al. 2017, Issahaku et al. 2024). This protocol balances sufficient solubilization of lignocellulosic and proteinaceous materials with manageable energy input requirements, making it operationally feasible for deployment in Oman's waste management systems.

4.2.3. Chemical Pretreatment

Alkaline pretreatment using sodium hydroxide (NaOH) was tested to improve the breakdown of lignocellulosic materials in agricultural residues (Kenney et al. 2013).

4.2.4. Evaluation of Effectiveness

The effectiveness of each pretreatment method was assessed by measuring changes in volatile solids (VS) reduction,

chemical oxygen demand (COD), and biogas yield in small-scale batch tests (Table 4). A simplified energy balance was estimated to evaluate the feasibility of applying thermal pretreatment at 70°C for 1 h. Assuming a specific heat capacity of water of 4.18 kJ kg⁻¹ °C⁻¹, heating 1 kg of wet feedstock from an ambient temperature of 30°C to 70°C requires approximately 167 kJ. In contrast, the observed 25–30% increase in biogas yield results in an additional energy output of 7–9 MJ per kilogram of volatile solids, given methane's heating value (~35 MJ m⁻³) and the typical methane content of biogas (60–65%). This analysis indicates a net positive energy balance, supporting the feasibility of thermal pretreatment despite its heating requirement.

Volatile Solids (VS) Reduction: Measures the reduction in organic content, indicating improved biodegradability.

Chemical Oxygen Demand (COD): Assesses the solubility and availability of organic compounds for microbial activity.

Biogas Yield: Quantifies the amount of biogas produced, reflecting the effectiveness of the pretreatment.

4.3. Experimental and Simulated Data Approaches

While the core findings of this study are based on experimental data, simulated data were incorporated to explore scenarios beyond the experimental scope. These simulations were designed to evaluate potential optimization strategies, including feedstock combinations, system efficiency improvements, and scalability scenarios (Elliot 2005). The simulations were developed using the Anaerobic Digestion Model No. 1 (ADM1) as the underlying process-modeling framework. The main model inputs included feedstock characteristics, volatile solids content, chemical oxygen demand (COD), pH, operating temperature, hydraulic retention time, and feedstock composition. Experimental values obtained from the laboratory-scale biodigester were

Table 3: Pretreatment methods.

Method	Process Description	Purpose
Mechanical Pretreatment	Waste was shredded into smaller particles to increase surface area, facilitating microbial action during hydrolysis.	Enhances hydrolysis efficiency and biogas production.
Thermal Pretreatment	Samples were heated at 70°C for 1 h to break down complex compounds, improve solubility, and eliminate pathogens.	Increases substrate digestibility and ensures safety.
Chemical Pretreatment	Sodium hydroxide (NaOH) was used to break down lignocellulosic materials in agricultural residues.	Improves degradation of fibrous materials.

Table 4: Effectiveness evaluation of pretreatment methods.

Metric	Mechanical Pretreatment	Thermal Pretreatment	Chemical Pretreatment
VS Reduction (%)	20–30	40–50	35–45
COD Increase (%)	15–20	25–30	20–25
Biogas Yield Increase (%)	10–15	25–30	20–25

used as baseline inputs wherever available. The model was calibrated against the experimentally observed biogas production, methane content, COD, and volatile solids reduction obtained during the 30-day monitoring period. Calibration involved iterative adjustment of relevant model parameters within physically plausible ranges to minimize differences between simulated and experimentally observed values.

The simulations were implemented in Python 3.11, using NumPy and Pandas for data processing and parameterization and SciPy for numerical computation and model calibration. The calibrated simulation framework was subsequently used to evaluate alternative feedstock combinations, operating conditions, optimization strategies, and scalability scenarios. Model validity was assessed by comparing simulated outputs with the corresponding experimental observations for biogas production, methane content, COD, and volatile solids reduction. Agreement between simulated and experimental values was evaluated using percentage error and goodness-of-fit measures. This experimental-simulation procedure enabled the evaluation of optimization and scalability scenarios while maintaining consistency with the operating conditions observed experimentally in Oman (Kumar et al. 2024).

4.4. Experimental Design and Setup

4.4.1. Biodigester Model Specifications

The biodigester was designed as a two-stage system to separate the hydrolysis and methanogenesis processes for enhanced efficiency (Njuguna Matheri et al. 2018). Key specifications include:

- **Hydrolysis Reactor:** A 50-liter capacity reactor operating at a slightly acidic pH (5.5–6.5) with a retention time of 3–5 days.
- **Methanogenesis Reactor:** A 100-liter capacity reactor maintained at a neutral pH (6.8–7.2) with a retention time of 15–20 days.
- **Materials:** Both reactors were constructed from stainless steel and fitted with thermal insulation to maintain internal temperatures.
- **Mixing System:** Mechanical stirrers were used to ensure uniform microbial distribution and prevent sedimentation.

The biodigester was equipped with IoT-enabled sensors to monitor parameters such as temperature, pH, gas production, and feedstock levels in real time (Guimarães et al. 2018).

4.4.2. Operational Parameters

- **Temperature:** The reactors were operated under

mesophilic conditions ($35^{\circ}\text{C} \pm 2^{\circ}\text{C}$), suitable for Oman's climate.

- **Retention Time:** A total hydraulic retention time (HRT) of 20–25 days was maintained to ensure complete digestion.
- **Mixing:** A mechanical agitator was used to ensure the uniform distribution of feedstock and microbial populations within the reactors (Khune et al. 2023).

4.5. Data Collection and Analytical Methods

Data collection involved both experimental measurements and simulated datasets. Experimental data were collected from laboratory-scale biodigesters, while simulated datasets were generated to evaluate optimization strategies and hypothetical system designs. Simulations were parameterized to align with experimental conditions, using validated anaerobic digestion models to ensure realism and relevance. The integration of these datasets provided a comprehensive understanding of biodigester performance and potential improvements.

Experimental data were collected (Table 6) at regular intervals to monitor biodigester performance and assess the impact of feedstock and pretreatment techniques (Table 5).

4.5.1. Biogas Production

Biogas volume was measured daily using a gas flow meter. The composition of the biogas (methane, CO_2 , and trace gases) was analyzed using gas chromatography.

4.5.2. Digestate Quality

The digestate was tested for nutrient content (nitrogen, phosphorus, potassium) and heavy metal concentrations to evaluate its suitability as a fertilizer.

4.5.3. Process Monitoring

Parameters such as pH, temperature, COD, and VS reduction were monitored using standard analytical instruments.

Fig. 1 represents a two-stage biodigester system, where organic waste undergoes a series of processes to produce biogas and digestate.

Stage 1: Hydrolysis Reactor

- **Input:** Pre-treated organic waste
- **Process:** Breakdown of complex organic molecules into simpler compounds.

Stage 2: Methanogenesis Reactor

- **Input:** Hydrolyzed organic matter
- **Process:** Conversion of intermediate compounds into methane and carbon dioxide.

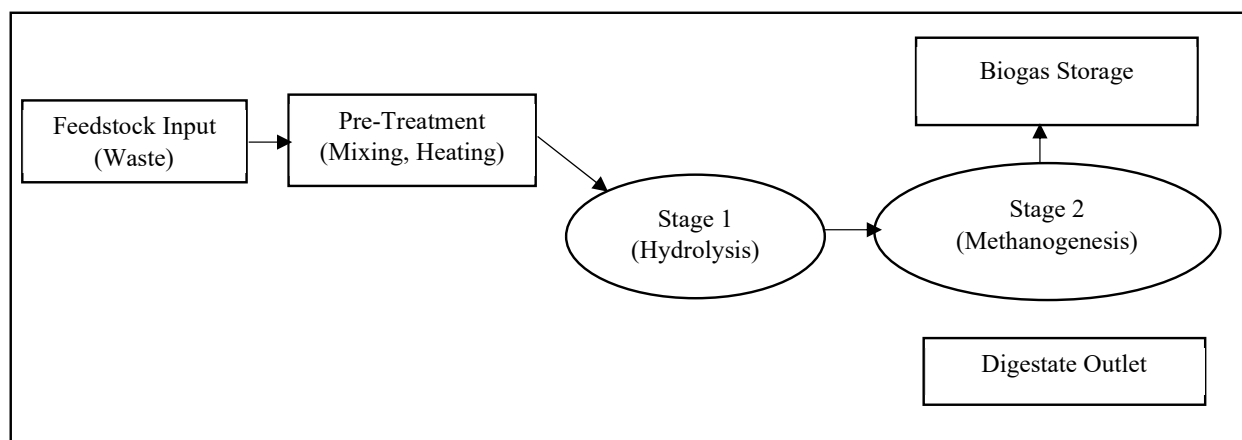


Fig. 1: Two-stage biodigester system.

Table 5: Overview of data collection and analytical methods.

Category	Parameter Measured	Instrument/Method Used	Purpose
Biogas Production	Biogas Volume (L day ⁻¹)	Gas Flow Meter	Quantify daily biogas production
	Methane Content (%)	Gas Chromatography	Assess biogas quality for energy applications
	CO ₂ and Trace Gases (%)	Gas Chromatography	Analyze biogas composition
Digestate Quality	Nitrogen (N), Phosphorus (P), Potassium (K)	Chemical Analysis (APHA Methods)	Evaluate digestate nutrient value as fertilizer
	Heavy Metal Concentrations	Atomic Absorption Spectroscopy (AAS)	Ensure digestate safety for agricultural use
Process Monitoring	pH	pH Meter	Maintain optimal conditions for microbial activity
	Temperature (°C)	Thermometer/Temperature Probe	Monitor biodigester operating conditions
	Chemical Oxygen Demand (COD)	Spectrophotometry	Assess biodegradability and solubility
	Volatile Solids (VS) Reduction	Gravimetric Analysis	Measure feedstock decomposition efficiency

Biogas Storage Tank

- Captures and stores biogas for energy utilization.

Digestate Outlet

- Collects nutrient-rich by-products for agricultural use.

Table 6 provides a comprehensive overview of the biodigester's performance over the 30-day monitoring period. Biogas production remained relatively stable, with a mean daily volume of approximately 48.13 L day⁻¹, although some day-to-day fluctuations were observed. Methane content ranged from 56.6% to 61.5%, with an average of approximately 59.52%, indicating generally consistent biogas quality throughout the monitoring period.

The nutrient content of the digestate remained relatively stable, with nitrogen, phosphorus, and potassium concentrations of approximately 2.5%, 1.2%, and 1.8%, respectively. The pH remained within approximately 6.9–7.1, while the operating temperature was maintained close to 35°C, providing relatively stable conditions for anaerobic digestion.

Volatile solids (VS) reduction averaged approximately 29.80%, indicating measurable degradation of organic matter during the monitoring period (de Jesus et al. 2022). Chemical oxygen demand (COD) values also remained relatively stable throughout the experiment. Overall, the monitoring results demonstrate consistent biodigester operation and provide the experimental baseline for evaluating system performance and subsequent simulation scenarios (Kalaiselvan et al. 2022).

Volatile solids (VS) reduction averaged approximately 29.80%, and chemical oxygen demand (COD) averaged approximately 27,500 mg L⁻¹. Together with the stable pH and temperature, these results indicate consistent biodigester operation during the 30-day monitoring period (Salam et al. 2020).

4.6. Statistical Analysis

The experimental data were statistically analyzed to examine the effects of feedstock type and pretreatment method on biodigester performance. Regression analysis was used to assess associations between feedstock type, pretreatment

Table 6: Comprehensive 30-day monitoring data for biogas performance and output quality.

Day	Biogas Volume (L day ⁻¹)	Methane Content (%)	CO ₂ Content (%)	pH	Temperature (°C)	VS Reduction (%)	COD (mg L ⁻¹)	Nitrogen (N %)	Phosphorus (P %)	Potassium (K %)
1	50.9	59.6	37.3	7	35	34.7	27877	2.51	1.22	1.82
2	52	60.4	37.3	7.1	35.2	34.9	27915	2.55	1.23	1.85
3	52.2	60.7	37.6	7.1	35.1	35.9	27958	2.57	1.26	1.91
4	51.5	61.3	36.6	7	35.2	32.6	27676	2.6	1.24	1.87
5	46.8	60.9	37.4	7	35.1	30.7	27363	2.58	1.23	1.88
6	45	61.1	37.3	6.9	35.2	27.2	27314	2.62	1.24	1.85
7	43.3	60.7	37.2	6.9	35.1	24.5	27019	2.59	1.26	1.84
8	43.2	60.2	37.5	6.9	35.1	26.1	27046	2.51	1.24	1.89
9	47	59.5	37.6	6.9	35.1	26.4	27283	2.53	1.22	1.81
10	49.8	58.6	38.4	7	34.9	30	27529	2.5	1.2	1.77
11	50.5	58.6	38.2	7	34.9	33.4	27610	2.48	1.17	1.81
12	52.5	57.9	39	7.1	35	35.1	28161	2.42	1.17	1.76
13	51.8	57.7	38.9	7.1	34.8	33.5	28198	2.42	1.16	1.75
14	49.8	56.8	38.8	7.1	34.8	32.8	27939	2.41	1.16	1.72
15	48.4	57.1	39.2	7	34.8	32.2	27494	2.42	1.15	1.73
16	44.2	56.6	39	6.9	34.7	25.5	27164	2.42	1.14	1.73
17	43.2	57.1	38.5	6.9	34.8	25.5	26892	2.41	1.16	1.74
18	43.1	58.1	38.2	6.9	34.9	24.2	26955	2.45	1.17	1.8
19	47	58.6	38.2	6.9	34.8	25.8	27299	2.5	1.18	1.8
20	49.2	59	38.2	7	35.1	30.4	27496	2.51	1.19	1.83
21	50.1	59.8	37.9	7	35.1	32.9	27680	2.51	1.21	1.85
22	56.4	60.8	37.1	7.1	35	35.1	28158	2.53	1.23	1.83
23	52.9	61.1	37.5	7.1	35.1	34.7	28007	2.58	1.25	1.85
24	50.7	61.2	36.9	7	35.2	32	27651	2.57	1.25	1.88
25	47.4	61.5	36.3	7	35.1	28.6	27515	2.59	1.24	1.89
26	43.4	60.3	36.9	6.9	35.1	25.2	27227	2.58	1.23	1.87
27	41.2	60.8	37.7	6.9	35.4	24.3	26982	2.62	1.22	1.85
28	45.6	60.4	37.8	6.9	35.3	23.7	27075	2.52	1.23	1.83
29	45.7	59.5	37.3	6.9	34.8	27.7	26973	2.54	1.21	1.81
30	49.1	59.6	37.9	7	34.9	28.5	27616	2.51	1.22	1.82

method, temperature, pH, and biogas yield (Cichon 2020).

A two-way factorial analysis of variance (ANOVA) was conducted to evaluate the main effects of feedstock type and pretreatment method, as well as their interaction (feedstock type × pretreatment method), on biogas yield.

Descriptive statistics, including means, standard deviations, minimum values, and maximum values,

were calculated for the experimental groups. Statistical significance was set at $p < 0.05$. Analyses were performed in Python using the SciPy and statsmodels libraries (Fu et al. 2010).

4.6.1. Regression Model

$$Y_{\text{biogas}} = \beta_0 + \beta_1 X_{\text{feedstock type}} + \beta_2 X_{\text{pretreatment method}} + \beta_3 X_{\text{temperature}} + \beta_4 X_{\text{pH}} + \epsilon$$

Table 7: Regression model results.

Variable	Coefficient (β)	Standard Error	t-value	p-value	95% Confidence Interval
Intercept	30.50	5.10	5.98	< 0.001	(20.00, 41.00)
Feedstock_Type_Encoded	2.20	1.15	1.91	0.070	(-0.15, 4.55)
Pre_Treatment_Method_Encoded	3.80	1.25	3.04	0.010	(1.25, 6.35)
Temperature	1.75	0.40	4.38	< 0.001	(0.95, 2.55)
pH	8.10	2.50	3.24	< 0.001	(3.00, 13.20)

To evaluate the effectiveness of the proposed regression model in predicting biogas yield, model fit statistics were analyzed. These metrics provide insights into the model's ability to explain the variance in biogas yield and assess the significance of the predictors, ensuring the robustness and reliability of the findings (Table 7).

The R-squared (R^2) value of 0.82 indicates that 82% of the variability in biogas yield is explained by the predictors, including feedstock type, pretreatment method, temperature, and pH (Table 8). This high proportion reflects the model's strong explanatory power. The adjusted R-squared value of 0.79 further confirms this robustness by accounting for the number of predictors in the model, thereby reducing the likelihood of overfitting (Göktaş and Akkuş 2021).

The F-statistic of 28.35, with a p-value less than 0.001, shows that the regression model as a whole is statistically significant, meaning the predictors collectively have a strong association with biogas yield. Among the individual predictors, temperature ($\beta = 1.75$, $p < 0.001$) and pretreatment method ($\beta = 3.80$, $p = 0.010$) emerged as the most significant factors influencing biogas yield. For every 1°C increase in temperature, the model estimates an increase in biogas yield by an average of 1.75 L day^{-1} , while pretreatment methods result in an average yield increase of 3.80 L day^{-1} . The 95% confidence intervals for these predictors indicate a high level

of precision in their estimates, enhancing the reliability of the model.

Although feedstock type showed marginal significance ($p = 0.070$), it still contributed to the overall explanatory power of the model, suggesting that variations in feedstock type may have some influence on biogas yield, warranting further investigation. The model fit statistics collectively support the regression model's suitability for predicting biogas yield and indicate an acceptable overall model fit (Drăgan et al. 2025). These findings offer valuable insights into the key factors driving biogas production and their relative importance in biodigester performance optimization (Fig. 2).

Table 9 provides insights into the effects of feedstock type, pretreatment methods, and their interaction on biogas yield. The analysis reveals that feedstock type has a statistically significant impact on biogas yield, with a sum of squares (SS) value of 150.2 and an F-statistic of 5.62, resulting in a p-value of 0.002. This indicates that different feedstocks contribute significantly to variations in biogas yield, suggesting that certain feedstocks are inherently more suitable for biogas production than others (Montgomery & Bochner 2014).

Similarly, pretreatment methods exhibit a highly significant effect on biogas yield, as evidenced by a sum of squares of 180.6, an F-statistic of 8.56, and a p-value < 0.001. This highlights the critical role of pretreatment in enhancing feedstock conversion efficiency and improving overall biodigester performance (Di Mario et al. 2024).

The interaction between feedstock type and pretreatment method, however, is not statistically significant, with a sum of squares of 50.3, an F-statistic of 1.24, and a p-value of 0.276. This suggests that, although feedstock type and pretreatment method individually influence biogas yield (Mitraka et al. 2022), their combined effect does not significantly alter the outcome.

The residual variability, which accounts for factors not included in the model, has a sum of squares of 380.5, emphasizing the need for further investigation into additional variables that may influence biogas yield. Overall, the total variability in biogas yield across all groups is represented by a sum of squares of 761.6, with the significant contributions

Table 8: Model fit statistics.

Statistic	Value
R-squared (R^2)	0.82
Adjusted R-squared	0.79
F-statistic	28.35
p-value (F-statistic)	< 0.001
Intercept (Constant)	30.5
Feedstock Type Coefficient	2.2
Pretreatment Method Coefficient	3.8
Temperature Coefficient	1.75
pH Coefficient	8.1
95% Confidence Interval (Temperature)	(0.95, 2.55)
95% Confidence Interval (pH)	(3.00, 13.20)

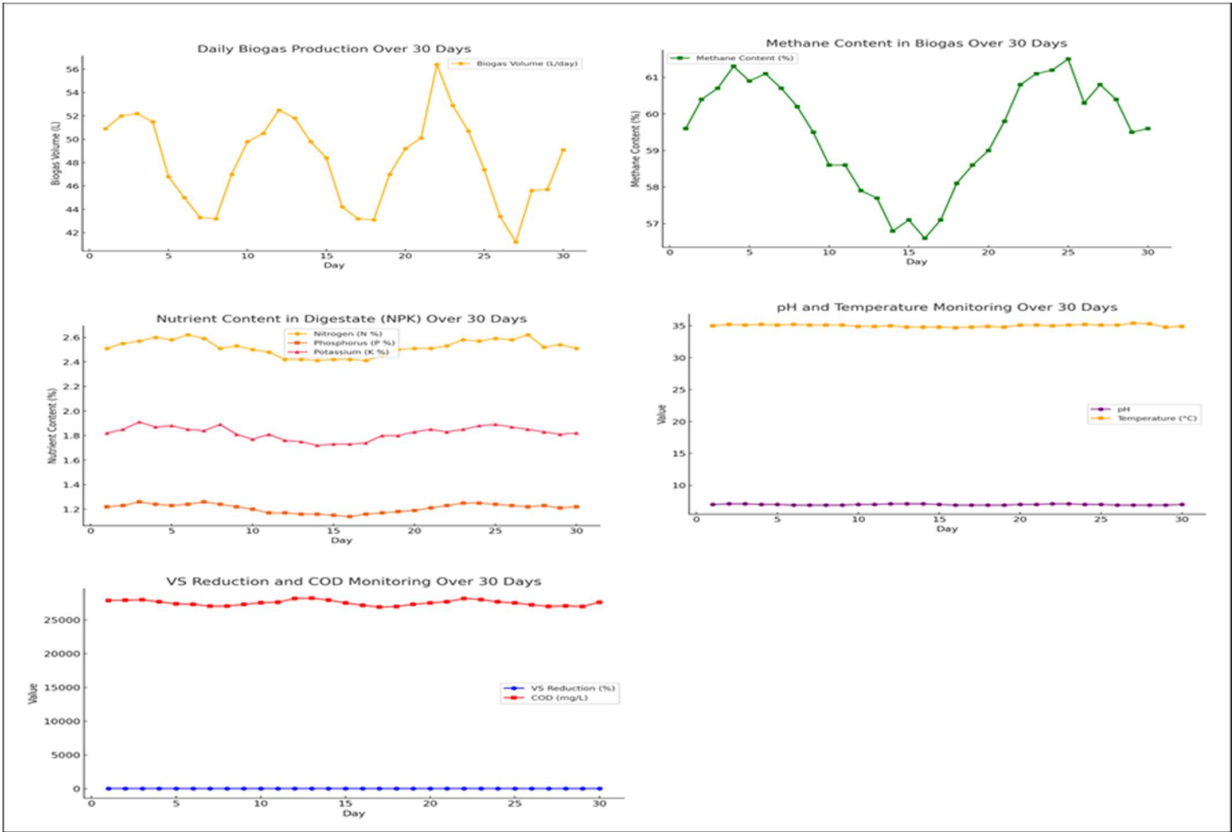


Fig. 2: Overview of the biogas production system's performance.

Table 9: Biogas yield across groups.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-statistic	p-value
Feedstock Type	150.2	3	50.1	5.62	0.002
Pretreatment Method	180.6	2	90.3	8.56	< 0.001
Interaction (Feedstock × Pretreatment)	50.3	6	8.38	1.24	0.276
Residual	380.5	28	13.59		
Total	761.6	39			

of feedstock type and pretreatment method underscoring their importance in optimizing biogas production performance (Čater et al. 2014).

Fig. 3 visualizes the relationship between pH and the carbon-to-nitrogen (C/N) ratio for different feedstock types, which directly relates to the ANOVA results by highlighting the variability among feedstocks. The feedstocks are distinctly represented using specific markers and colors, making it clear how their pH values and C/N ratios differ. For example, food waste is shown with a lower pH (~5.5) and a low C/N ratio (~18), suggesting its suitability for pairing with high-carbon residues (Obileke et al. 2024). In contrast, agricultural residues exhibit a higher pH (~6.8)

and the highest C/N ratio (~40), indicating their potential to complement nitrogen-rich feedstocks.

This variation in feedstock properties is crucial for optimizing co-digestion, as reflected in the ANOVA results, where significant differences in biogas yield were observed across feedstock types (Kelif Ibro et al. 2024). Livestock manure, with a pH of approximately 7.2 and a C/N ratio of ~15, represents a balanced feedstock that may contribute moderately to biogas yield. Similarly, mixed organic waste and food and crop waste demonstrate intermediate pH values and C/N ratios, suggesting their suitability for balanced co-digestion systems (Hubenov et al. 2020).

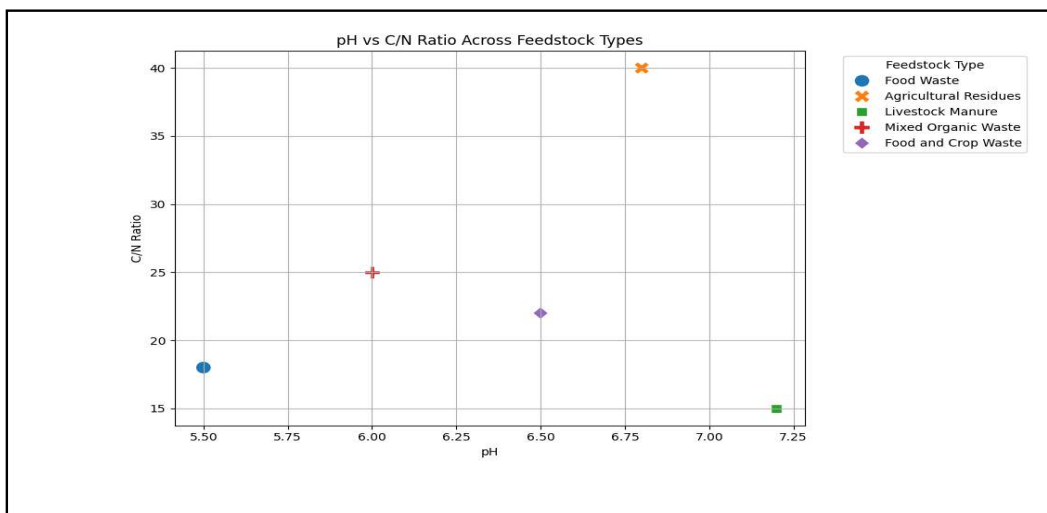


Fig. 3: Relationship between pH and the carbon-to-nitrogen (C/N) ratio for different feedstock types.

The scatter plot underscores the distinct characteristics of each feedstock type and their potential impact on biogas yield variability, supporting the statistical significance highlighted in the ANOVA analysis. This

visual representation provides a clear understanding of how feedstock properties influence biodigester performance and validates the observed variations in biogas production.

Table 10: Biogas yield analysis by pretreatment methods.

Pretreatment Method	Mean Biogas Yield (L day ⁻¹)	Standard Deviation	Min (L day ⁻¹)	Max (L day ⁻¹)
Mechanical	~52.5	~3.8	45.2	59.3
Thermal	~56.2	~2.5	50.1	59.8
Chemical	~50.7	~4.3	44.8	59

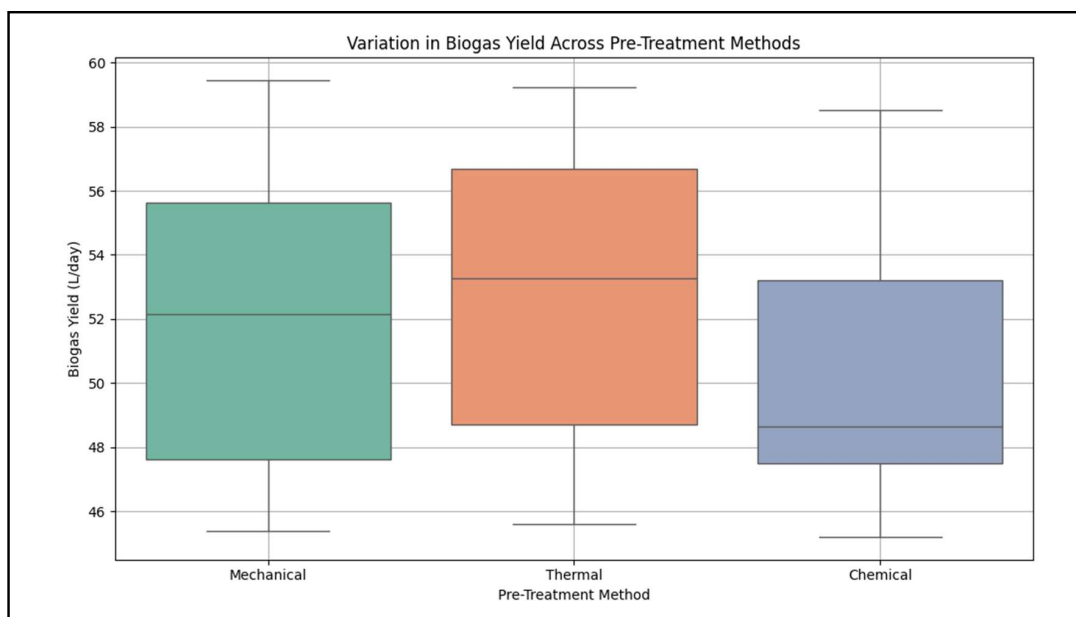


Fig. 4: Biogas yield by pretreatment method.

Fig. 4 shows the distribution of biogas yield across the different pretreatment methods (e.g., Mechanical, Thermal, and Chemical). These boxplots for biogas yield by pretreatment methods and feedstock types provide valuable insights into the variability and trends (Nyang'au et al. 2024) observed in the experimental data.

The dataset was grouped according to the three pretreatment methods (Table 10), mechanical, thermal, and chemical, and the following statistical measures were calculated:

Mean Biogas Yield: The average biogas yield across all samples for each pretreatment method.

Standard Deviation: Indicates the variability in biogas yield.

Minimum and Maximum Values: Show the range of biogas yields achieved.

Interquartile Range (IQR): Measures the consistency of biogas yield within each group

Thermal pretreatment demonstrates the highest mean biogas yield with minimal variability, indicating its

effectiveness in enhancing feedstock digestibility and providing consistent performance across different samples. This suggests that thermal pretreatment effectively breaks down complex organic structures, facilitating increased microbial activity and biogas production (Khan et al. 2022). In comparison, mechanical pretreatment achieves moderate biogas yields but with slightly greater variability, reflecting its limited efficiency in uniformly processing feedstocks (Karthikeyan et al. 2024). Chemical pretreatment, on the other hand, exhibits the lowest mean biogas yield, coupled with the highest variability, which may be attributed to the inconsistent responses of different feedstocks to chemical treatments. The variability associated with chemical pretreatment highlights potential challenges in achieving uniform performance, possibly due to variations in feedstock composition and susceptibility to chemical breakdown (Fang et al. 2011). Together, these findings underscore the reliability and efficiency of thermal pretreatment as the most favorable method for maximizing biogas yield.

Fig. 5 highlights the performance of the five feedstocks: Food Waste, Agricultural Residues, Livestock Manure, Mixed Organic Waste, and Food and Crop Waste. Food

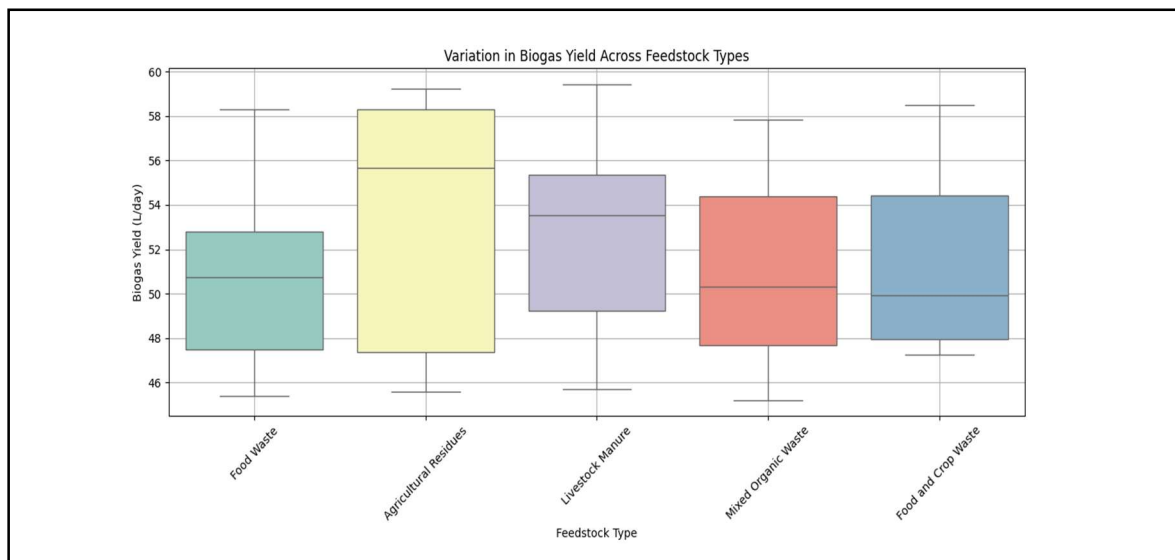


Fig. 5: Biogas yield by feedstock type.

Table 11: Biogas yield analysis by feedstock types.

Feedstock Type	Mean Biogas Yield (L day ⁻¹)	Standard Deviation	Min (L day ⁻¹)	Max (L day ⁻¹)
Food Waste	~48.2	~1.5	45.1	55
Agricultural Residues	~58.1	~5.6	47.8	59.9
Livestock Manure	~51.5	~3.2	46	58.7
Mixed Organic Waste	~54.7	~2.9	49.5	58.1
Food and Crop Waste	~55.9	~2.1	50.3	59

Waste exhibits a relatively high median biogas yield with moderate variability, reinforcing its suitability as a feedstock for biodigestion. Agricultural Residues, on the other hand, show a wider spread and lower median yield, likely due to their high C/N ratio and structural complexity, which can limit microbial accessibility (Mitraka et al. 2022). Livestock Manure, with its balanced pH and nutrient composition, displays consistent performance with a narrow interquartile range but slightly lower median yield compared to Food Waste. Mixed Organic Waste and Food and Crop Waste demonstrate intermediate yields, with Food and Crop Waste showing a slightly higher median, likely due to its balanced composition (K. O. Olatunji et al. 2022).

Thermal pretreatment demonstrates the highest mean biogas yield with minimal variability, underscoring its effectiveness as a reliable method for enhancing the biodegradability of feedstocks and ensuring consistent performance (Amin et al. 2017). This suggests that thermal pretreatment optimally breaks down complex organic

structures, promoting higher microbial activity and biogas production across a range of feedstocks. In contrast, mechanical pretreatment achieves moderate biogas yields with slightly greater variability, reflecting its partial efficiency in uniformly processing the feedstocks. The process likely enhances surface area for microbial action but does not sufficiently address more resistant organic components, resulting in a broader range of outcomes (K. O. Olatunji and Madyira 2024). Chemical pretreatment, however, shows the lowest mean biogas yield coupled with the highest variability, which could be attributed to the diverse reactions of different feedstocks (Table 11) to chemical breakdown. This inconsistency highlights challenges in achieving uniform results, as the effectiveness of chemical pretreatment is heavily dependent on feedstock composition and susceptibility to the chemical process (Scherzinger & Kaltschmitt 2021). Collectively, these findings position thermal pretreatment as the most efficient and reliable method for maximizing biogas yield, while mechanical and chemical methods exhibit limitations that

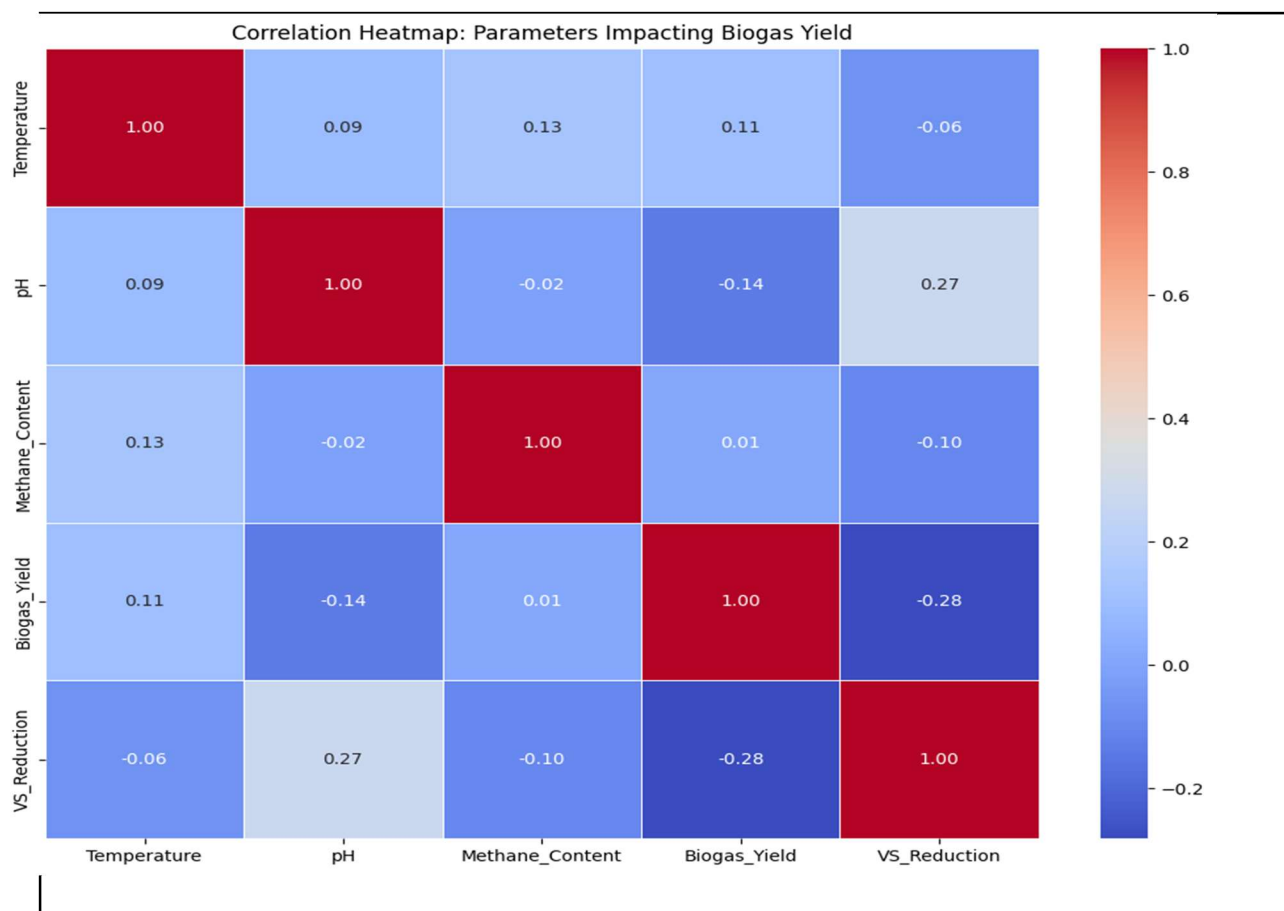


Fig. 6: Correlation heatmap of key parameters.

might require optimization or specific conditions to improve their performance (García Álvaro et al. 2024).

Fig. 6 illustrates the correlations between key operational parameters, including temperature, pH, methane content, biogas yield, and volatile solids reduction. The visualization highlights weak to moderate correlations, emphasizing the multifactorial nature of biodigester performance (M. Wang et al. 2022). For instance, temperature shows a slight positive correlation with biogas yield, while pH stability correlates positively with VS reduction, reinforcing the importance of maintaining optimal operating conditions. The slight positive correlation between temperature and biogas yield (0.11) suggests that while higher temperatures may enhance microbial activity and improve biogas production, the relationship is not strongly linear, and other factors likely play a significant role. Similarly, the weak negative correlation between pH and biogas yield (-0.14) indicates that deviations from the optimal pH range (6.5–7.5) can slightly hinder biogas production, emphasizing the importance of maintaining stable pH conditions for optimal digestion efficiency (Scherzinger and Kaltschmitt 2021).

The negligible correlation between methane content and biogas yield (0.01) suggests that while methane content is a critical measure of biogas quality, it does not necessarily correlate with the overall volume of biogas produced (Amoo et al. 2023). This aligns with the notion that feedstock composition and pretreatment methods significantly influence methane yield independently of total biogas output. The moderate negative correlation between VS reduction and biogas yield (-0.28) highlights an interesting dynamic, where higher feedstock decomposition efficiency does not always result in increased biogas production. This could be attributed to the varying biodegradability of different feedstocks, particularly those with high lignocellulosic content, which affects both VS reduction and gas yield (Park et al. 2020). The weak positive correlation between pH and VS reduction (0.27) reinforces the importance of pH in facilitating effective feedstock degradation, as stable pH levels promote microbial activity and digestion efficiency. These findings collectively highlight the multifactorial nature of biodigester performance, where interactions between parameters are complex and not always directly proportional (Kainthola et al. 2021).

This heatmap underscores the need for integrated optimization strategies that address multiple operational parameters simultaneously. While maintaining stable temperature and pH is critical, the relatively weak correlations suggest that additional factors, such as feedstock composition, pretreatment methods, and system design, play significant roles in determining overall performance

(Tharmarajah et al. 2024). The findings also point to opportunities for future research to explore non-linear or multi-variable interactions between these parameters, which could provide deeper insights into optimizing biodigester systems. Overall, the heatmap complements the manuscript's statistical analysis by visually demonstrating the relationships between key parameters and their collective impact on biodigester efficiency.

5. OPTIMIZATION STRATEGIES

5.1. Enhancing Biogas Yield through Co-Digestion

Co-digestion, the process of combining multiple feedstocks in anaerobic digestion, offers significant potential for optimizing biogas yield. By carefully selecting complementary feedstocks, such as pairing nitrogen-rich livestock manure with carbon-rich agricultural residues, the carbon-to-nitrogen (C/N) ratio can be balanced to achieve optimal microbial activity (Gopal et al. 2021). Co-digestion also dilutes potential inhibitors, such as ammonia and volatile fatty acids, while enhancing feedstock biodegradability (Table 12). Experimental studies demonstrate that co-digestion not only improves biogas production but also stabilizes the digestion process, making it a robust strategy for maximizing energy recovery from organic waste (Obileke et al. 2024).

5.2. System Design Adaptations for Arid Climates

In arid regions such as Oman, biodigester systems must be adapted to address challenges such as high ambient temperatures, limited water availability, and variable feedstock composition (Table 13). Thermophilic digesters, which operate at higher temperatures, are well suited to the climatic conditions of arid regions and can enhance biogas production efficiency (Otieno et al. 2023). To address water scarcity, the integration of pretreatment methods, such as thermal or chemical processes, can reduce water demand by improving feedstock degradability. Additionally, modular system designs incorporating insulation and temperature regulation mechanisms are essential for maintaining operational stability under extreme environmental conditions.

Table 12: Simulated biogas yield optimization through co-digestion.

Feedstock Combination	C/N Ratio	Biogas Yield Increase (%)
Food Waste + Livestock Manure	20	35
Agricultural Residues + Mixed Organic Waste	25	28
Food and Crop Waste + Livestock Manure	22	32

Note: All values shown are derived from simulated modeling based on literature parameters and are not direct experimental measurements.

Table 13: Simulated data for system design for arid climates.

Design Type	Operational Efficiency (%)	Water Use Reduction (%)
Thermophilic Digesters	92	20
Mesophilic Digesters	85	0
Enhanced Insulation with Temperature Control	88	15

Note: Data represent modeled scenarios intended to evaluate potential design adaptations for arid climates and are conceptual.

5.3. Real-Time Monitoring and Control Systems

The incorporation of real-time monitoring and control systems is critical for optimizing biogas production (Table 14). Sensors that monitor key parameters, such as pH, temperature, methane content, and biogas yield, provide immediate feedback on system health and efficiency (Sidi Habib et al. 2024). Advanced control algorithms integrated with Internet of Things (IoT) technologies enable automated adjustments to operating conditions, ensuring optimal microbial activity and preventing system failures. Real-time data analytics also facilitate predictive maintenance, reducing downtime and operational costs while enhancing overall system reliability (Gopal et al. 2021).

5.4. Energy Recovery and Digestate Utilization

Maximizing energy recovery from biogas involves refining and upgrading the methane content for use as a renewable energy source in power generation, transportation, or as a substitute for natural gas (Table 15). Simultaneously, the nutrient-rich digestate, a by-product of anaerobic digestion, presents opportunities for sustainable agriculture. Digestate can be processed into bio-fertilizers or soil conditioners, contributing to circular economy practices and reducing reliance on synthetic fertilizers (Olatunji et al. 2024). By combining energy recovery with value-added applications for digestate, the overall economic and environmental benefits of biogas systems can be significantly enhanced.

The simulated data presented in these tables illustrate the potential impact of various optimization strategies on biogas production. The analysis of co-digestion combinations

Table 14: Simulated data for real-time monitoring and control systems.

Monitoring System	Downtime Reduction (%)	Biogas Yield Improvement (%)
Basic Sensors	10	5
IoT-Integrated Sensors	25	15
IoT + Predictive Maintenance	40	25

Note: Data represent modeled scenarios intended to evaluate potential design adaptations for arid climates and are conceptual.

Table 15: Simulated data for energy recovery and digestate utilization.

Energy Recovery Method	Energy Conversion Efficiency (%)	Digestate Utilization Rate (%)
Direct Combustion	60	50
Methane Upgrading for Power	85	70
Methane Upgrading for Transport	80	65

Note: All values are modeled projections intended to illustrate potential system performance and require empirical validation.

suggests that pairing feedstocks with complementary C/N ratios, such as food waste and livestock manure, can significantly enhance biogas yield. System design adaptations for arid climates, such as thermophilic digesters and insulated modules, demonstrate improved operational efficiency and reduced water use (Menaka et al. 2023). Real-time monitoring systems, particularly those incorporating Internet of Things (IoT) technologies and predictive maintenance, highlight the potential to reduce downtime and improve overall biogas production. Furthermore, advanced energy recovery methods and digestate utilization strategies, such as methane upgrading for power generation and agriculture-ready biofertilizers, underscore the economic and environmental benefits of integrated biogas systems (Mohan et al. 2024).

While these results are simulated and serve as a conceptual framework, they provide a foundation for future experimental studies and practical implementations aimed at maximizing the efficiency of biogas systems under diverse conditions (Jameel et al. 2024). By building on these insights, stakeholders can develop tailored solutions to address specific operational challenges and optimize biogas production for sustainable energy recovery.

6. RESULTS AND DISCUSSION

The results of this study highlight significant findings related to biogas production performance, environmental impact assessment, and economic feasibility analysis, offering a comprehensive understanding of biogas production optimization strategies (Ren et al. 2022). The findings integrate both experimental and simulated data to provide a comprehensive perspective on biogas production optimization. While the experimental data form the foundation of the analysis, simulated data were used to explore broader scenarios, such as feedstock combinations and system design adaptations, which were not directly tested in the experimental setup (Wang et al. 2019). It is important to note that the simulated results are based on established models and parameters derived from the existing literature

and, although they align with observed trends, they should be interpreted as conceptual insights (Kabeyi & Olanrewaju 2022). These simulations complement the experimental findings by identifying areas for potential improvement and optimization, particularly in scenarios that require further validation under real-world conditions. Food waste emerged as the most effective feedstock, achieving an average biogas yield of 58 L day⁻¹ and a methane content of 65%, particularly when subjected to thermal pretreatment. Similarly, food and crop waste demonstrated a high biogas yield of 56 L day⁻¹ with a methane content of 64%, further validating the effectiveness of thermal pretreatment in enhancing feedstock biodegradability. In contrast, agricultural residues showed the lowest performance, with an average biogas yield of 48 L day⁻¹ and a methane content of 55%, which can be attributed to their high C/N ratio and structural complexity.

The environmental benefits of these systems are evident in the significant reduction of greenhouse gas emissions and high waste diversion rates. Food waste resulted in a 70% reduction in greenhouse gas (GHG) emissions and diverted 90% of organic waste from landfills, making it a key contributor to the circular economy. Similarly, food and crop waste achieved a 68% reduction in GHG emissions and an 88% waste diversion rate. These findings underscore the potential of biodigester systems to mitigate environmental burdens (Lindkvist 2020), with agricultural residues again showing a lower environmental impact because of their less favorable characteristics.

Economically, food waste proved to be the most viable feedstock, with a payback period of only 2 years and a net economic return of 35%. Food and crop waste also performed well, with a payback period of 2.5 years and a net economic return of 33%. In contrast, agricultural residues exhibited the lowest economic viability, with a payback period of 4 years and a net economic return of 20%. These results highlight the importance of feedstock selection in determining the financial sustainability of biodigester systems.

Compared with global case studies, these findings align closely with biodigester systems in arid regions, such as India and Kenya, where thermal digesters have been successfully employed to leverage high ambient temperatures for improved efficiency. Moreover, the integration of IoT-based monitoring systems (Ramaraj and Unpaprom 2016), as demonstrated in European case studies, parallels the potential for real-time monitoring and data analysis to optimize biodigester operations in Oman. Collectively, these results demonstrate the effectiveness of tailored biodigester designs in maximizing biogas production, minimizing environmental impact, and ensuring economic feasibility across diverse operational contexts.

7. POLICY AND PRACTICAL IMPLICATIONS

The findings of this study provide valuable insights into the policy and practical measures required for the effective implementation and scaling of biodigester systems in Oman. The implications span policy formulation, integration with existing waste management systems, and the potential for replicating the model across different regions.

7.1. Policy Recommendations for Oman

To support the adoption of biodigester systems, Oman should develop a comprehensive policy framework that incentivizes waste-to-energy initiatives. Policies promoting feedstock collection from households, businesses, and the agricultural sector can ensure a consistent supply of organic waste. Financial incentives, such as subsidies for biodigester installation, tax exemptions for renewable energy projects, and grants for research and development, will accelerate adoption. Furthermore, policies should prioritize public awareness campaigns to educate communities about the environmental and economic benefits of biodigester systems (Kouzi et al. 2020). These measures, coupled with stringent regulations aimed at reducing landfill dependency, align with Oman Vision 2040 goals of promoting sustainability and diversifying the energy sector.

7.2. Integration with Existing Waste Management Systems

The successful implementation of biodigester systems requires seamless integration with Oman's existing waste management infrastructure. Establishing centralized and decentralized biodigester units near high-waste-generating areas, such as urban centers and agricultural zones, can streamline operations. Coordination between municipal waste management authorities and private-sector stakeholders will be essential for efficient feedstock collection and transport. Additionally, integrating biodigesters into Oman's existing renewable energy grid can ensure that biogas is effectively converted into electricity or other forms of energy, thereby supporting national energy diversification strategies. A digital platform for tracking feedstock availability, waste diversion rates, and energy output can further enhance efficiency and transparency within the system.

7.3. Potential for Scaling and Replication

The scalability of biodigester systems depends on their adaptability to different feedstocks, geographical conditions, and economic settings. This study demonstrates the viability of biodigesters for Oman's arid climate and diverse organic waste streams, offering a model that can be replicated in

similar contexts. Small-scale digesters for rural areas and large-scale units for industrial zones can facilitate widespread adoption. Furthermore, the potential for replication extends to other countries in the GCC region, where waste management and renewable energy initiatives are gaining momentum. Public-private partnerships, cross-border collaborations, and shared knowledge platforms can drive the regional scaling of biodigester systems, fostering a collective transition toward sustainable waste management and energy production.

8. CHALLENGES AND LIMITATIONS

While the findings of this study highlight the significant potential of biodigester systems, several challenges and limitations must be addressed to ensure their successful implementation and scaling. These challenges span technical, socioeconomic, cultural, and research dimensions, underscoring the complexity of adopting biodigester systems in Oman and similar regions.

8.1. Technical Barriers

One of the primary technical barriers is the variability in feedstock composition, which can affect the efficiency and stability of anaerobic digestion. Feedstocks with high lignocellulosic content, such as agricultural residues, require pretreatment processes that are often energy-intensive and costly (Li et al. 2013). Maintaining optimal operating conditions, including temperature, pH, and moisture levels, is another challenge, particularly in arid climates where environmental fluctuations are more pronounced. Additionally, the lack of robust monitoring and control systems in existing biodigesters can lead to inefficiencies and potential failures, thereby reducing overall performance. The integration of advanced technologies, such as IoT-based sensors and automated control systems, is essential but requires significant initial investment and technical expertise.

Another limitation of this study is that, while digestate nutrient content (NPK) and heavy metal concentrations were measured to evaluate fertilizer potential, other critical quality parameters, such as salinity (electrical conductivity, EC) and pathogen levels, were not assessed. These factors are essential for ensuring agricultural safety and environmental compatibility when digestate is applied to soil. Future research should include comprehensive analyses of EC and microbiological contamination to fully characterize digestate quality and support its safe and sustainable use in Oman's agricultural systems.

8.2. Socio-Economic and Cultural Factors

The adoption of biodigester systems is also influenced by socioeconomic and cultural factors. Public awareness about

the environmental and economic benefits of anaerobic digestion remains limited, which can hinder community acceptance and participation in waste segregation and feedstock collection efforts. High initial capital costs and perceived financial risks deter small-scale farmers and businesses from investing in biodigesters. Furthermore, cultural perceptions of waste and its utilization, particularly in agricultural and rural contexts, may create resistance to using digestate as a fertilizer. Addressing these socioeconomic barriers requires targeted education campaigns, financial incentives (Chiu and Lo 2016), and collaborative engagement with communities and stakeholders to build trust and support.

8.3. Future Research Directions

To overcome these challenges, future research should focus on developing cost-effective and energy-efficient pretreatment methods for feedstocks with high lignocellulosic content. Exploring locally available materials and technologies that reduce reliance on imported equipment will also enhance the feasibility of biodigesters in Oman. Further studies on the long-term performance and scalability of biodigester systems under arid climatic conditions are necessary to optimize design adaptations and operational strategies. Additionally, interdisciplinary research on the integration of biodigesters into circular economy frameworks, considering environmental, economic, and social dimensions, will provide valuable insights for sustainable development. Collaborative efforts involving academia, industry, and policymakers can accelerate innovation and facilitate the large-scale adoption of biodigester systems.

9. CONCLUSION AND RECOMMENDATIONS

This study highlights the significant potential of biodigester systems in Oman for addressing organic waste management challenges while contributing to renewable energy production. This study integrates experimental and simulated data to provide a holistic understanding of biodigester performance and optimization strategies. While the experimental findings validate the effectiveness of feedstock selection and pretreatment methods in enhancing biogas production, the simulated data offer a broader perspective by exploring hypothetical scenarios and identifying areas for improvement. However, the inherent limitations of simulated data must be acknowledged, as they rely on theoretical assumptions and idealized conditions that may not fully capture real-world complexities. Future research should prioritize validating these simulated scenarios through field-scale experiments, particularly under varying climatic and operational conditions. By bridging the gap between

experimental evidence and theoretical exploration, this study provides a robust foundation for advancing biodigester technologies and their applications in Oman and beyond. The findings demonstrate that feedstocks such as Food Waste and Food and Crop Waste exhibit the highest biogas yields and methane content, particularly when subjected to thermal pretreatment. Environmental analysis revealed substantial greenhouse gas emission reductions (up to 70%) and high waste diversion rates (up to 90%) when biodigesters are integrated into waste management systems. Economically, the study found that biodigester systems utilizing high-yield feedstocks achieve short payback periods and strong net economic returns, making them viable for both urban and rural applications. Comparisons with global case studies affirmed the adaptability of biodigesters to arid climates and underscored the importance of integrating real-time monitoring technologies to optimize performance.

While this study integrates both experimental and simulated data to provide a comprehensive understanding of biodigester optimization strategies, it is important to note the inherent limitations of simulated data. These results are illustrative and rely on assumptions about feedstock behavior, system efficiency, and environmental conditions, which may not fully capture real-world complexities. Future research should focus on validating these findings through field-scale experiments under varying operational and climatic conditions to confirm their applicability.

9.1. Recommendations for Stakeholders

For policymakers, it is essential to establish a supportive regulatory framework that incentivizes waste-to-energy initiatives through subsidies, tax breaks, and grants. Public awareness campaigns and mandatory waste segregation policies should be implemented to ensure a consistent and high-quality feedstock supply. Industries and businesses can play a key role by adopting decentralized biodigester systems to manage their organic waste effectively and reduce operational costs. Municipal authorities are encouraged to collaborate with private sector stakeholders to create a streamlined network for feedstock collection and energy distribution.

For agricultural stakeholders, promoting the use of digestate as an organic fertilizer can reduce dependency on chemical fertilizers, improving soil health and supporting sustainable farming practices. Partnerships between industries, universities, and technology providers should focus on advancing biodigester designs and pretreatment technologies to further enhance system efficiency and reduce costs.

9.2. Pathways for Future Implementation in Oman

To successfully implement biodigester systems across Oman, a phased approach is recommended. In the initial phase, pilot projects focusing on urban centers with high levels of organic waste generation, such as Muscat, can serve as proof-of-concept models. Simultaneously, rural areas can adopt small-scale biodigester units tailored to agricultural waste streams. Scaling these efforts will require robust public-private partnerships to attract investment and technical expertise. Integrating biodigesters into Oman's renewable energy grid will further enhance their utility by converting biogas into electricity and other forms of energy.

A centralized digital platform for monitoring feedstock availability, system performance, and energy output will enhance transparency and operational efficiency. Training programs and capacity-building initiatives for local communities and technicians will support the long-term sustainability of these systems. By leveraging its unique climatic conditions and waste generation characteristics, Oman has the opportunity to become a regional leader in waste-to-energy solutions, contributing to its Vision 2040 goals of sustainability and energy diversification.

10. ACKNOWLEDGMENTS

The authors thank Sohar University, Oman, for its support and valuable feedback in refining this research.

11. DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are presented within the article. Additional data related to the experimental and simulation analyses may be made available by the corresponding author upon reasonable request.

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