Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

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

Jasim Abdullah ali Al Shehhi† and Nitin Bhaurao Raut

Faculty of Engineering, Sohar University, Sohar, Oman

†Corresponding author: Jasim Abdullah ali Al Shehhi

ORCID IDs of Authors: 0009-0007-4015-9234

0000-0003-1370-0965

Key Words	Biodigester optimization, Anaerobic digestion, Organic waste management, Renewable energy, Sustainable development, Greenhouse gas reduction
DOI	https://doi.org/10.46488/NEPT.2026.v25i04. D1824 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Al Shehhi, J. A. A. and Raut, N. B., 2026. Organic waste to energy: Enhancing biodigester efficiency in oman for sustainable development. *Nature Environment and Pollution Technology*, 25(4), D1824. https://doi.org/10.46488/NEPT.2026.v25i04. D1824

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 and waste profiles. Utilizing a mixed-methods approach that integrates experimental data (30-day monitoring of five feedstock types) with simulated scenarios, the research evaluates five feedstock types (Food Waste, Agricultural Residues, Livestock Manure, Mixed Organic Waste, and Food and Crop Waste) and three pre-treatment methods (Mechanical, Thermal, and Chemical). The findings demonstrate that thermal pre-treatment enhances biogas yield by up to 25-30%, with Food Waste and Food and Crop Waste achieving the highest methane content (65% and 64%, respectively). Environmental analysis reveals substantial benefits, including up to 70% greenhouse gas emissions reduction and 90% waste diversion rates. Economically, biodigesters utilizing high-yield feedstocks achieve short payback periods of 2–2.5 years, with net economic returns exceeding 30%. Simulated data highlight the potential for co-digestion, system adaptations for arid climates, and real-time monitoring technologies to further enhance performance. The study aligns with Oman's Vision 2040 by providing actionable insights into sustainable waste management and renewable energy integration. By addressing technical, environmental, and economic dimensions, the research offers a scalable and replicable model for advancing biodigester systems in Oman.

1. INTRODUCTION

The global shift towards sustainable energy solutions has underscored the critical need to address organic waste management challenges. 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 like Oman, where unique climatic conditions and waste profiles demand 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 (Akhiar et al., 2020). Aligning with Oman's Vision 2040 sustainability goals, there is a pressing need to adopt innovative technologies (Ahmad & 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, pre-treatment, and system design (AL-Huqail et al., 2022) tailored to Oman's arid climate and waste characteristics. By integrating two-stage bio digestion processes—hydrolysis and methanogenesis—the research aims to maximize biogas yield and ensure the sustainable management of organic waste (AlQattan et al., 2018). Additionally, the valorization of digestate as a nutrient-rich fertilizer aligns with the country's agricultural development objectives, further promoting 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 is generated annually, with an estimated 60% of this categorized as organic (Ayodele et al., 2017). Mismanagement of organic waste poses critical environmental and health risks, including methane emissions, groundwater contamination, and inefficient resource utilization (Ayodele et al., 2018). Traditional disposal methods such as landfilling and open dumping 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 & 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's Vision 2040

Oman's 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 like 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 more hydrogen and carbon dioxide.
- Methanogenesis is the final stage, where 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, 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 over the conditions in each phase (Vaneeckhaute et al., 2018). This separation addresses one of the major challenges in single-stage digesters: the incompatibility of optimal conditions for hydrolytic and methanogenic microorganisms (Carrere et al., 2016).

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 slightly acidic pH and shorter retention times (Zheng & Li, 2024). By isolating this phase, the process efficiency is improved, and the risk of system instability is reduced.

Stage 2: Methanogenesis Reactor

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

Two-stage systems are particularly advantageous in 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 choice for optimizing biodigester performance (Nkemka et al., 2014), particularly in challenging climates such as Oman's.

3.3. Advances in Biodigester Design and Efficiency

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

1. Enhanced Pre-Treatment Technologies

Techniques such as thermal, chemical, and mechanical pre-treatment improve the digestibility of feedstocks, accelerating the hydrolysis process and increasing 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 like 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, 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).

5. High-Solid Anaerobic Digestion (HSAD)

HSAD systems are designed for feedstocks with high solid content, minimizing water usage—a critical advantage in arid regions like 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 in Oman (Table 1).

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

- **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: 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)

The 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.

4.2. Pre-Treatment Techniques for Organic Waste

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

Mechanical Pre-Treatment:

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

Thermal Pre-Treatment:

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

Thermal pre-treatment at 70 °C for 1 hour 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.

Chemical Pre-Treatment:

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

Table 3: Pre-Treatment Methods

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

Evaluation of Effectiveness:

The effectiveness of each pre-treatment method was assessed by measuring changes in 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 viability of applying thermal pre-treatment at 70 °C for 1 hour. Assuming a specific heat capacity of water (4.18 kJ/kg °C), heating 1 kg of wet feedstock from ambient temperature (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 kg volatile solids, given methane's heating value (~35 MJ/m³ and typical biogas methane content of 60–65%). This analysis indicates a net positive energy balance, supporting the feasibility of thermal pre-treatment despite its heating requirement.

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

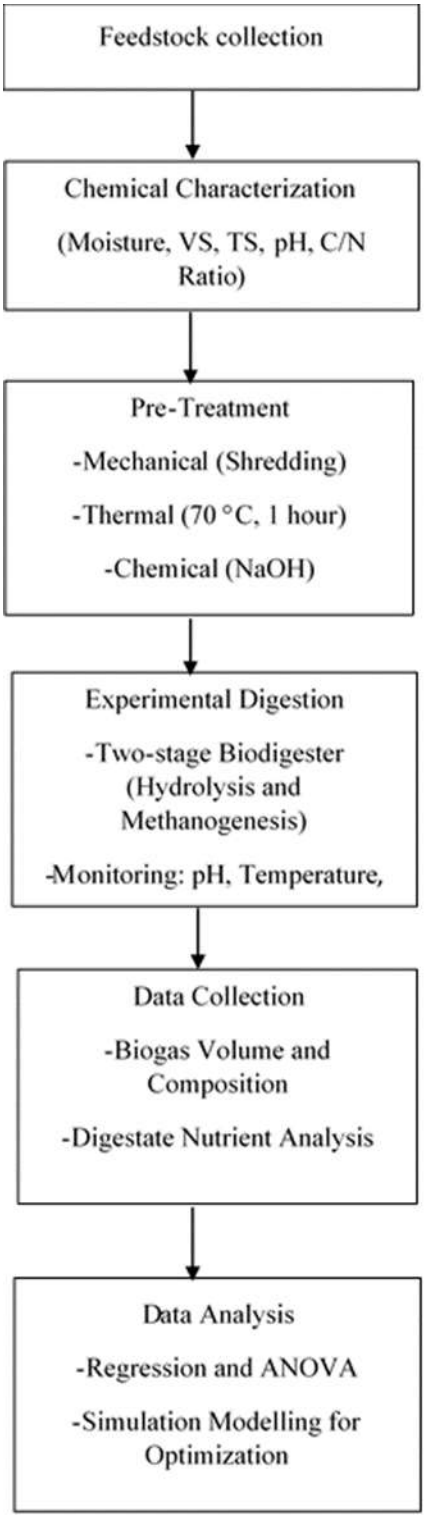
Chemical Oxygen Demand (COD): Assesses the solubility and availability of organic compounds for microbial action.

Biogas Yield: Quantifies the biogas produced, reflecting the effectiveness of the pre-treatment.

Table 4: Effectiveness Evaluation of Pre-Treatment Methods

Metric	Mechanical Pre-Treatment	Thermal Pre-Treatment	Chemical Pre-Treatment
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

Process Flow Diagram



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 simulated datasets were parameterized using established models of anaerobic digestion and calibrated to reflect realistic conditions relevant to Oman. This approach ensures that both experimental validation and theoretical exploration contribute to the study's conclusions(Kumar et al., 2024).

This study employed a mixed-methods approach, integrating experimental data from controlled laboratory setups with simulated data generated to evaluate hypothetical optimization strategies. Experimental methods focused on analyzing biogas yield and pre-treatment effects on five feedstock types. Simulated data, developed using established models and literature-based parameters, were used to explore broader scenarios, including co-digestion strategies, system adaptations, and scaling potential (Yousefi-Nasab et al., 2024).

4.4. Experimental Design and Setup

Biodigester Model Specifications

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

- **Hydrolysis Reactor**: A 50-liter capacity reactor operating at slightly acidic pH (5.5–6.5) and 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 with thermal insulation to maintain internal temperatures.
- **Mixing System**: Mechanical stirrers 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).

Operational Parameters

- **Temperature**: The reactors were operated at mesophilic conditions (35°C ± 2°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 uniform distribution of feedstock and microbial populations in 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 pre-treatment techniques (Table 5).

Biogas Production:

Biogas volume was measured daily using a gas flow meter. The composition of the biogas (methane, CO2, and trace gases) was analyzed using gas chromatography.

Digestate Quality:

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

Process Monitoring:

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

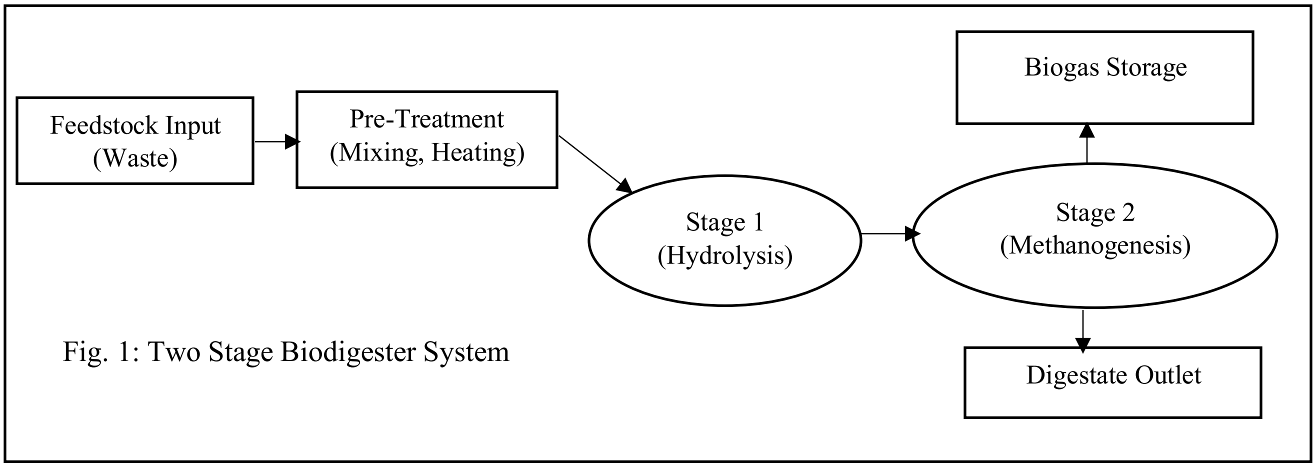


Fig. 1: Two Stage Biodigester System

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

Biogas Storage Tank

- Captures and stores biogas for energy utilization.

Digestate Outlet

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

Table 5: Overview of Data Collection and Analytical Methods

Category	**Parameter Measured**	**Instrument/Method Used**	**Purpose**
Biogas Production	Biogas Volume (L/day)	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

Table 6: Comprehensive 30-Day Monitoring Data for Biodigester Performance and Output Quality

Day	**Biogas Volume (L/day)**	**Methane Content (%)**	**CO_2, Content (%)**	**pH**	**Temperature (°C)**	**VS Reduction (%)**	**COD (mg/L)**	**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

Table 6 provides a comprehensive overview of the biodigester's performance over 30 days. Biogas production demonstrated consistent daily volumes, averaging around 52.5 liters, with minor fluctuations indicating stable feedstock digestion and efficient operation (Aridi & Yehya, 2024). Methane content in the biogas remained stable, ranging between 59–61%, reflecting high-quality biogas suitable for energy applications (Kalaiselvan et al., 2022). This stability highlights the effectiveness of the digestion process in maintaining optimal gas composition (de Jesus et al., 2022).

The nutrient content in the digestate, specifically nitrogen (~2.5%), phosphorus (~1.2%), and potassium (~1.8%), remained consistent throughout the monitoring period. These levels confirm the digestate's suitability as a nutrient-rich fertilizer for agricultural applications. The pH values were maintained within the optimal range of 6.8–7.2, and the temperature stabilized around 35°C, ensuring ideal conditions for microbial activity and anaerobic digestion efficiency.

In terms of feedstock decomposition, the volatile solids reduction averaged approximately 35%, indicating effective organic matter breakdown. Simultaneously, the chemical oxygen demand (COD) values, averaging around 27,500 mg/L, demonstrated the system's ability to handle and biodegrade organic waste efficiently. Collectively, these results confirm the biodigester's stable performance, efficient waste processing, and quality output for energy and agricultural applications (Salam et al., 2020).

4.6 Statistical Analysis

The data collected during the study were statistically analyzed to understand the relationships between feedstock type, pre-treatment methods, and biodigester performance metrics. Regression models were employed to determine the impact of independent variables (e.g., feedstock type and pre-treatment method) on dependent variables such as biogas yield and methane content (Cichoń, 2020). These models allowed for the quantification of the influence of feedstock properties and processing techniques on system performance.

To evaluate the variability in outcomes across different pre-treatment methods, a one-way Analysis of Variance (ANOVA) was conducted. The ANOVA test assessed whether significant differences existed in biogas yield, volatile solids reduction, and nutrient content (NPK) in the digestate among the three pre-treatment groups (mechanical, thermal, and chemical)(Fu et al., 2010).

All statistical tests were performed using Python's SciPy and Stats models libraries. Results were considered statistically significant at a threshold of $p < 0.05$. Data are presented as means ± standard deviations, with graphical representations (e.g., error bars) used to illustrate variability and statistical significance (Goldin et al., 1996).

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	0.07	(-0.15, 4.55)
Pre_Treatment_Method_Encoded	3.80	1.25	3.04	0.01	(1.25, 6.35)
Temperature	1.75	0.40	4.38	< 0.001	(0.95, 2.55)
pH	8.10	2.50	3.24	0.00	(3.00, 13.20)

4.6.1 Regression Model

$$Y_{\text{biogas}}=\beta_0 + \beta_1 X_{\text{feedstock type}} + \beta_2 X_{\text{pre-treatment method}} + \beta 3 X_{\text{temperature}} + \beta_4 X_{\text{pH}} + \epsilon$$

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).

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
Pre-Treatment 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)

The R-squared (R^2) value of 0.82 indicates that 82% of the variability in biogas yield is accounted for by the predictors, including feedstock type, pre-treatment 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, reducing the likelihood of overfitting (Göktaş & 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 ($\beta=1.75$, $p<0.001$β=1.75, p<0.001) and pre-treatment method ($\beta=3.80$, $p=0.005$β=3.80, p=0.005) emerged as the most significant factors influencing biogas yield. For every 1°C increase in temperature, biogas yield increases by an average of 1.75 L/day, while pre-treatment methods result in an average yield increase of 3.80 L/day. The 95% confidence intervals for these predictors indicate a high level of precision in their estimates, enhancing the reliability of the model.

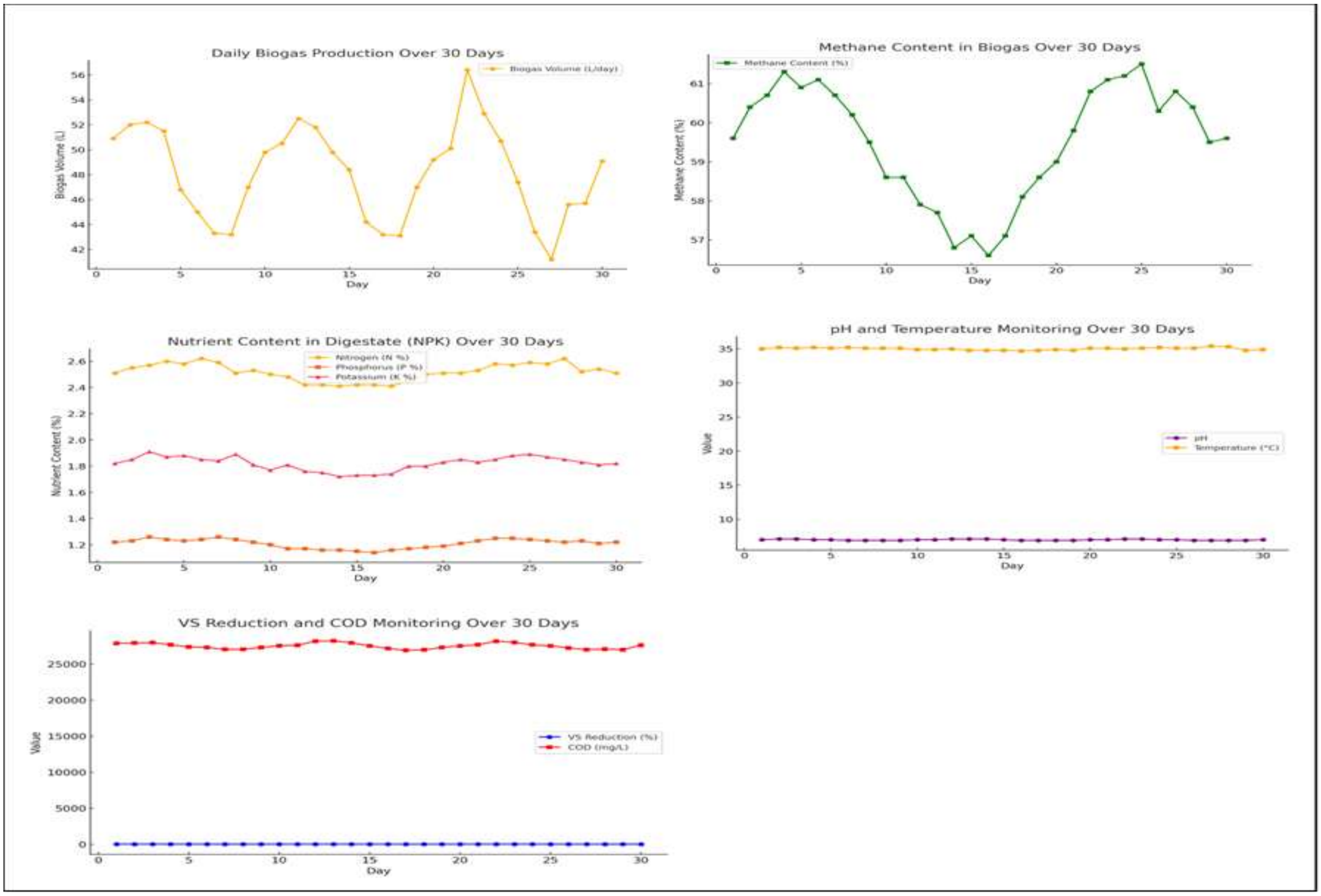


Fig. 2: Overview of the biodigester's performance

Although feedstock type showed marginal significance (p=0.067p=0.067), 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 validate the regression model's suitability for predicting biogas yield and provide confidence in the robustness of the results (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: 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

Pre-Treatment Method	180.6	2	90.3	8.56	<0.001
Interaction (Feedstock × Pre-Treatment)	50.3	6	8.38	1.24	0.276
Residual	380.5	28	13.59		
Total	761.6	39			

Table 9 provide insights into the effects of feedstock type, pre-treatment 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 & Bochmann, 2014).

Similarly, pre-treatment 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 of less than 0.001. This highlights the critical role of pre-treatment in enhancing the efficiency of feedstock conversion and improving overall biodigester performance (Di Mario et al., 2024).

The interaction between feedstock type and pre-treatment 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 while feedstock type and pre-treatment method individually influence biogas yield (Mitraka et al., 2022), their combined effect does not significantly alter the outcome.

The residual variability, accounting 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 might influence biogas yield. Overall, the total variability in biogas yield across all groups is captured by a sum of squares of 761.6, with the significant contributions of feedstock type and pre-treatment method underscoring their importance in optimizing biodigester 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 with specific markers and colors, making it clear how their pH 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). On the other hand, 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 seen 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 around 7.2 and a C/N ratio of ~15, represents a balanced feedstock type that might contribute moderately to biogas yield. Similarly, Mixed Organic Waste and Food and Crop Waste demonstrate intermediate values for pH and C/N ratio, suggesting their suitability for balanced co-digestion setups (Hubenov et al., 2020).

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.

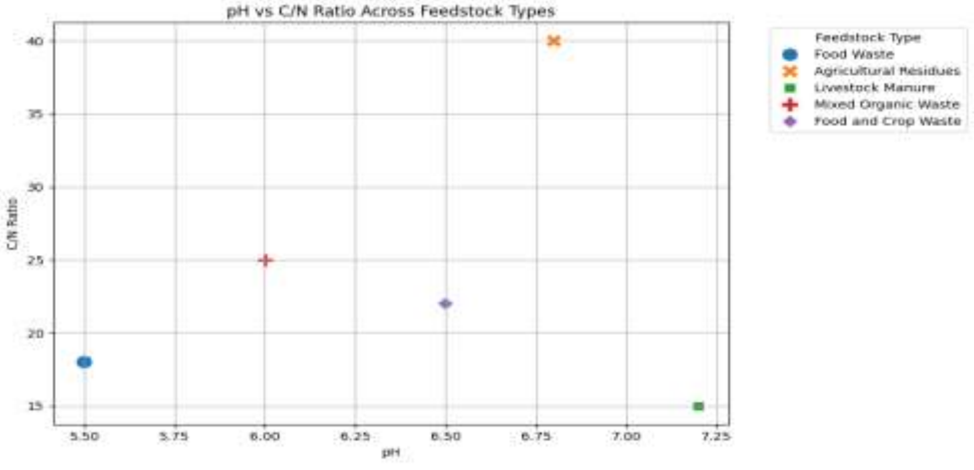


Fig. 3: Relationship between pH and the carbon-to-nitrogen (C/N) ratio for different feedstock types

In the Fig. 4 boxplot shows the distribution of biogas yield across the different pre-treatment methods (e.g., Mechanical, Thermal, and Chemical). These boxplots for biogas yield by pre-treatment 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 by the three pre-treatment methods (Table 10): Mechanical, Thermal, and Chemical, and statistical measures were calculated, including:

Mean Biogas Yield: The average yield across all samples for each pre-treatment.

Standard Deviation: Indicates variability in biogas yield.

Minimum and Maximum Values: Shows the range of yields achieved.

Interquartile Range (IQR): Measures consistency within the group.

Table 10: Biogas Yield Analysis by Pre-Treatment Methods

Pre-Treatment Method	**Mean Biogas Yield (L/day)**	**Standard Deviation**	**Min (L/day)**	**Max (L/day)**
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

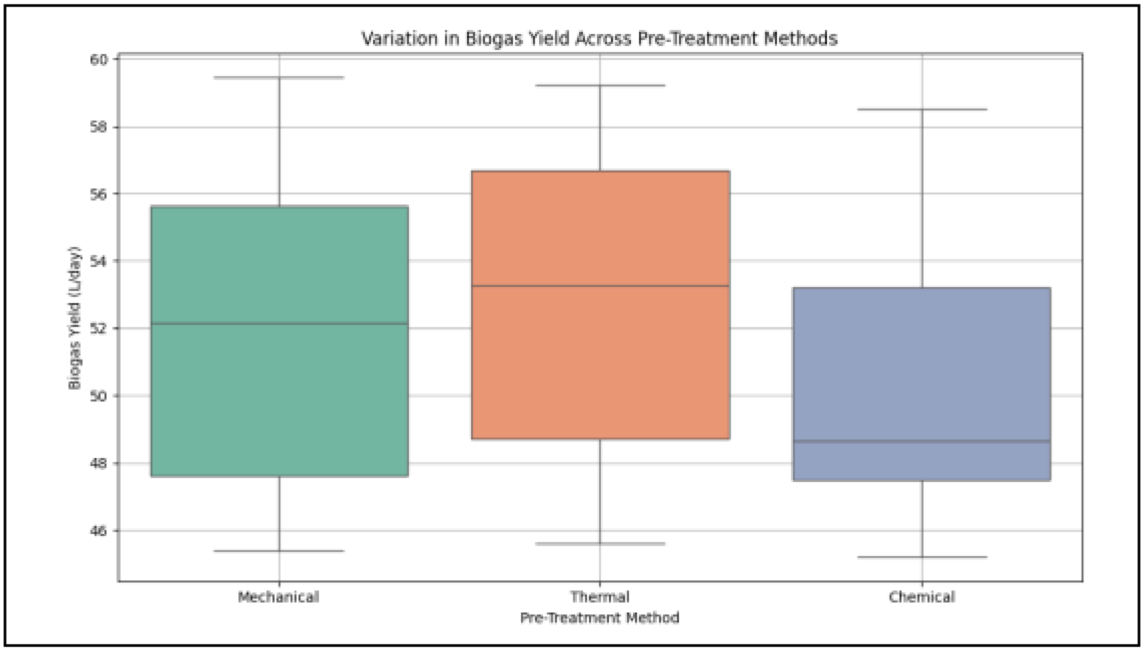


Fig. 4: Biogas yield pre-treatment methods

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

In the Fig. 5 boxplot for biogas yield by feedstock types highlights the performance of the five feedstocks: Food Waste, Agricultural Residues, Livestock Manure, Mixed Organic Waste, and Food and Crop Waste. Food Waste exhibits a relatively high median biogas yield with moderate variability, reinforcing its suitability as a feedstock for bio digestion. Agricultural Residues, on the other hand, show a wider spread and lower median yield, likely due to its 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).

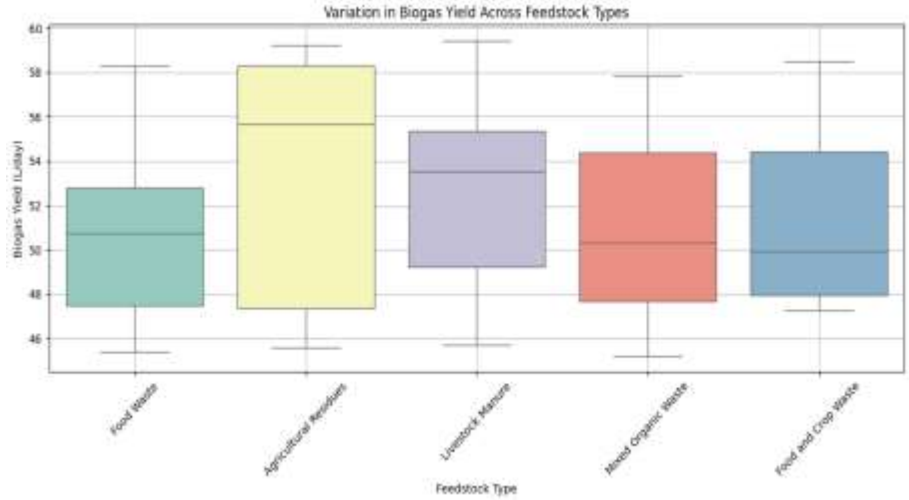


Fig. 5: Biogas yield by feedstock types

Table 11: Biogas Yield Analysis by Feedstock Types

Feedstock	Mean Biogas Yield	Standard	Min (L/day)	Max
Food Waste	~58.1	~1.5	55	59.9
Agricultural Residues	~48.2	~5.6	45.1	58.5

Livestock Manure	~51.5	~3.2	46	58
Mixed Organic Waste	~54.7	~2.9	47.8	58.7
Food and Crop Waste	~55.9	~2.1	50.3	59

Thermal pre-treatment 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 pre-treatment optimally breaks down complex organic structures, promoting higher microbial activity and biogas production across a range of feedstocks. In contrast, mechanical pre-treatment 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 & Madyira, 2024). Chemical pre-treatment, 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 pre-treatment is heavily dependent on feedstock composition and susceptibility to the chemical process (Scherzinger & Kaltschmitt, 2021). Collectively, these findings position thermal pre-treatment as the most efficient and reliable method for maximizing biogas yield, while mechanical and chemical methods exhibit limitations that might require optimization or specific conditions to improve their performance (García Álvaro et al., 2024).

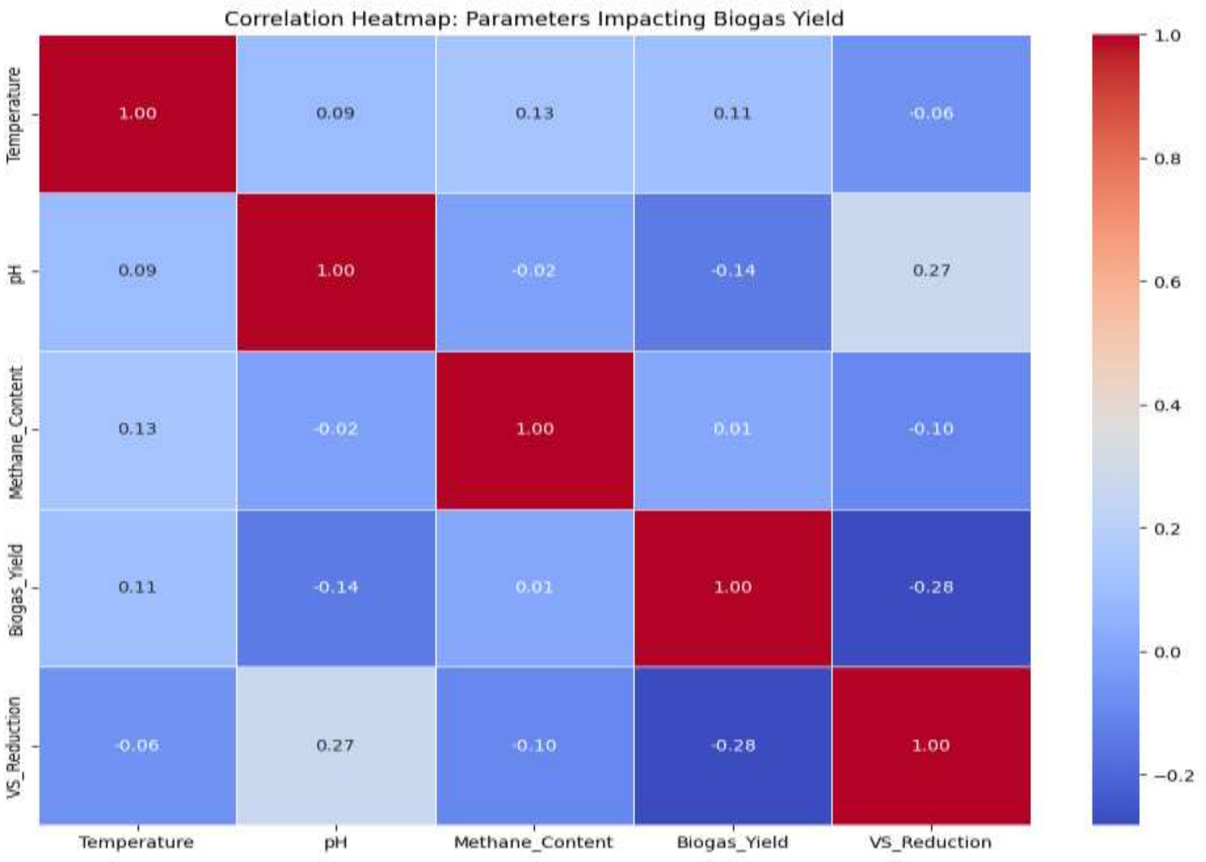


Fig. 6: Correlation heatmap of key parameters

Heatmap illustrating (Fig. 6) 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 & 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 pre-treatment 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, pre-treatment 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 or volatile fatty acids, and enhances the biodegradability of feedstocks (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).

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.

5.2. System Design Adaptations for Arid Climates

In arid regions, like 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, align well with the climatic conditions of arid zones and can enhance biogas production efficiency (Otieno et al., 2023). To address water scarcity, the integration of pre-treatment methods, such as thermal or chemical processes, can reduce water demand by improving feedstock degradability. Additionally, modular system designs that incorporate insulation and temperature regulation mechanisms are essential for maintaining operational stability under extreme environmental conditions.

Table13: 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 biodigester performance (Table 14). Sensors for tracking 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).

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.

5.4. Energy Recovery and Digestate Utilization

Maximizing energy recovery from biogas involves refining and upgrading the Thermal l 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 byproduct 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 the reliance on synthetic fertilizers (O. O. Olatunji et al., 2024). By combining energy recovery with value-added applications for digestate, the overall economic and environmental benefits of biodigester systems can be significantly enhanced.

Table15: 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.

The simulated data presented in these tables illustrate the potential impact of various optimization strategies on biogas production. The analysis of co-digestion combinations 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 water-use reduction (Menaka et al., 2023). Real-time monitoring systems, particularly those incorporating IoT 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 biodigester 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 in 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 across biogas production performance, environmental impact assessment, and economic feasibility analysis, offering a comprehensive understanding of biodigester optimization strategies (Ren et al., 2022). The results integrate both experimental and simulated data to provide a comprehensive perspective on biodigester optimization. While 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 (S. Wang et al., 2019). It is important to note that the simulated results are based on established models and parameters derived from existing literature, and while 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 and a methane content of 65%, particularly when subjected to thermal pre-treatment. Similarly, Food and Crop Waste demonstrated a high biogas yield of 56 L/day with a methane content of 64%, further validating the efficacy of thermal pre-treatment in enhancing feedstock biodegradability. In contrast, Agricultural Residues showed the lowest performance, with an average yield of 48 L/day and a methane content of 55%, which can be attributed to its 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 led to a 70% reduction in GHG emissions and diverted 90% of the organic waste from landfills, making it a key contributor to the circular economy. Similarly, Food and Crop Waste achieved a 68% reduction in emissions and an 88% diversion rate. These findings underscore the potential of biodigester systems to mitigate environmental burdens (Lindkvist, 2020), with Agricultural Residues again showing lower impact due to its 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 return of 33%. On the other hand, Agricultural Residues had the least economic viability, with a payback period of 4 years and a net return of 20%. These results highlight the importance of feedstock selection in determining the financial sustainability of biodigester systems.

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

7. POLICY AND PRACTICAL IMPLICATIONS

The findings of this study provide valuable insights into the policy and practical measures necessary for the effective implementation and scaling of biodigester systems in Oman. The implications span policy formulation, integration with current 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 agricultural sectors 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 must 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 to reduce landfill dependency, align with Oman’s 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 current 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, the integration of biodigesters into Oman's existing renewable energy grid can ensure that biogas is effectively converted into electricity or other energy forms, supporting national energy diversification strategies. A digital platform to track feedstock availability, waste diversion rates, and energy outputs can further enhance efficiency and transparency in 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. The 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 ensure widespread adoption. Furthermore, the replication potential 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, socio-economic, 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 pre-treatment 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, 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 applying digestate to soils. Future research should include comprehensive analyses of EC and microbiological contamination to fully characterize digestate quality and support safe, sustainable use in Oman's agricultural systems.

8.2. Socio-Economic and Cultural Factors

The adoption of biodigester systems is also influenced by socio-economic 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 socio-economic barriers requires targeted education campaigns, financial incentives (Chiu & 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 pre-treatment methods for feedstocks with high lignocellulosic content. Exploring locally available materials and technologies that can 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 pre-treatment 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 pre-treatment. 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 pre-treatment 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 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 energy forms.

A centralized digital platform for monitoring feedstock availability, system performance, and energy outputs will ensure transparency and operational efficiency. Training programs and capacity-building initiatives for local communities and technicians will support the long-term sustainability of the systems. By leveraging its unique climatic 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.

Acknowledgements

The authors express their gratitude to Sohar University, Oman, for their support and valuable feedback in refining this research.

References

Ahmad, M., & Wu, Y. (2022). Household-based factors affecting uptake of biogas plants in Bangladesh: Implications for sustainable development. *Renewable Energy*, *194*, 858–867. https://doi.org/https://doi.org/10.1016/j.renene.2022.05.135

Amin, F. R., Khalid, H., Zhang, H., Rahman, S. u., Zhang, R., Liu, G., & Chen, C. (2017). Pretreatment methods of lignocellulosic biomass for anaerobic digestion. AMB Express, 7(1), 72. https://doi.org/10.1186/s13568-017-0375-4

Akhiar, A., Ahmad Zamri, M. F. M., Torrijos, M., Shamsuddin, A. H., Battimelli, A., Roslan, E., Mohd Marzuki, M. H., & Carrere, H. (2020). Anaerobic digestion industries progress throughout the world. *IOP Conference Series: Earth and Environmental Science*, *476*(1), 12074. https://doi.org/10.1088/1755-1315/476/1/012074

AL-Huqail, A. A., Kumar, V., Kumar, R., Eid, E. M., Taher, M. A., Adelodun, B., Abou Fayssal, S., Mioč, B., Držaić, V., Goala, M., Kumar, P., & Širić, I. (2022). Sustainable Valorization of Four Types of Fruit Peel Waste for Biogas Recovery and Use of Digestate for Radish (Raphanus sativus L. cv. Pusa Himani) Cultivation. In *Sustainability* (Vol. 14, Issue 16). https://doi.org/10.3390/su141610224

AlQattan, N., Acheampong, M., Jaward, F. M., Ertem, F. C., Vijayakumar, N., & Bello, T. (2018). Reviewing the potential of Waste-to-Energy (WTE) technologies for Sustainable Development Goal (SDG) numbers seven and eleven. *Renewable Energy Focus*, *27*, 97–110. https://doi.org/https://doi.org/10.1016/j.ref.2018.09.005

Amin, F. R., Khalid, H., Zhang, H., Rahman, S. u., Zhang, R., Liu, G., & Chen, C. (2017). Pretreatment methods of lignocellulosic biomass for anaerobic digestion. *AMB Express*, *7*(1), 72. https://doi.org/10.1186/s13568-017-0375-4

Amoo, A., Madu, I., Haruna, A., Adeleye, A., & Sabo, A. (2023). Review on the Pre-treatment Advancements of Biogas Production Barriers. *UMYU Journal of Microbiology Research (UJMR)*, *8*, 6–30. https://doi.org/10.47430/ujmr.2381.002

Ampese, L. C., Sganzerla, W. G., Di Domenico Ziero, H., Mudhoo, A., Martins, G., & Forster-Carneiro, T. (2022). Research progress, trends, and updates on anaerobic digestion technology: A bibliometric analysis. *Journal of Cleaner Production*, *331*, 130004. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.130004

Amuzu-Sefordzi, B., Martinus, K., Tschakert, P., & Wills, R. (2018). Disruptive innovations and decentralized renewable energy systems in Africa: A socio-technical review. *Energy Research & Social Science*, *46*, 140–154. https://doi.org/https://doi.org/10.1016/j.erss.2018.06.014

Aridi, R., & Yehya, A. (2024). Anaerobic biodigesters heating sources: Analysis and recommendations. *Renewable and Sustainable Energy Reviews*, *202*, 114700. https://doi.org/https://doi.org/10.1016/j.rser.2024.114700

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2017). Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. *Applied Energy*, *201*, 200–218. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.05.097

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2018). Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. *Journal of Cleaner Production*, *203*, 718–735. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.08.282

Barbera, E., Bertucco, A., Nigam, K. D. P., & Kumar, S. (2022). Techno-economic analysis of a micro-scale biogas plant integrated with microalgae cultivation for the treatment of organic municipal waste. *Chemical Engineering Journal*, *450*, 138323. https://doi.org/https://doi.org/10.1016/j.cej.2022.138323

Bywater, A., Heaven, S., Zhang, Y., & Banks, C. J. (2022). Potential for Biomethanisation of CO2 from Anaerobic Digestion of Organic Wastes in the United Kingdom. In *Processes* (Vol. 10, Issue 6). https://doi.org/10.3390/pr10061202

Carrere, H., Antonopoulou, G., Affes, R., Passos, F., Battimelli, A., Lyberatos, G., & Ferrer, I. (2016). Review of feedstock pretreatment strategies for improved anaerobic digestion: From lab-scale research to full-scale application. *Bioresource Technology*, *199*, 386–397. https://doi.org/https://doi.org/10.1016/j.biortech.2015.09.007

Čater, M., Zorec, M., & Marinšek Logar, R. (2014). Methods for Improving Anaerobic Lignocellulosic Substrates Degradation for Enhanced Biogas Production. *Springer Science Reviews*, *2*(1), 51–61. https://doi.org/10.1007/s40362-014-0019-x

Chen, L., Fang, W., Liang, J., Nabi, M., Cai, Y., Wang, Q., Zhang, P., & Zhang, G. (2023). Biochar application in anaerobic digestion: Performances, mechanisms, environmental assessment and circular economy. *Resources, Conservation and Recycling*, *188*, 106720. https://doi.org/https://doi.org/10.1016/j.resconrec.2022.106720

Chiu, S. L. H., & Lo, I. M. C. (2016). Reviewing the anaerobic digestion and co-digestion process of food waste from the perspectives on biogas production performance and environmental impacts. *Environmental Science and Pollution Research*, *23*(24), 24435–24450. https://doi.org/10.1007/s11356-016-7159-2

Cichoń, M. (2020). Reporting statistical methods and outcome of statistical analyses in research articles. *Pharmacological Reports*, *72*(3), 481–485. https://doi.org/10.1007/s43440-020-00110-5

de Jesus, M. A. S., Aguiar Dutra, A. R. de, Cirani, C. B. S., Jesus, K. R. E., Neto, R. C. S., & Guerra, J. B. A. (2022). Eco-innovation assessment of biodigesters technology: an application in cassava processing industries in the south of Brazil, Parana state. *Clean Technologies and Environmental Policy*, *24*(3), 931–948. https://doi.org/10.1007/s10098-021-02232-7

de Souza Guimarães, C., & da Silva Maia, D. R. (2023). Development of Anaerobic Biodigester for the Production of Biogas Used in Semi-Continuous System Bioprocesses: An Efficient Alternative for Co-Digestion of Low Biodegradability Biomass. In *Biomass* (Vol. 3, Issue 1, pp. 18–30). https://doi.org/10.3390/biomass3010002

Di Mario, J., Montegiove, N., Gambelli, A. M., Brienza, M., Zadra, C., & Gigliotti, G. (2024). Waste Biomass Pretreatments for Biogas Yield Optimization and for the Extraction of Valuable High-Added-Value Products: Possible Combinations of the Two Processes toward a Biorefinery Purpose. In *Biomass* (Vol. 4, Issue 3, pp. 865–885). https://doi.org/10.3390/biomass4030048

Drăgan, C. O., Mihai, L. S., Popescu, A.-M. C., Buligiu, I., Mirescu, L., & Militaru, D. (2025). Statistical Analysis and Forecasts of Performance Indicators in the Romanian Healthcare System. In *Healthcare* (Vol. 13, Issue 2). https://doi.org/10.3390/healthcare13020102

Dubois, O., Pirelli, T., & Peressotti, A. (2019). *13 - Biomass anaerobic digestion and gasification in non-OECD countries—an overview* (M. Materazzi & P. U. B. T.-S. N. G. from W. Foscolo (eds.); pp. 343–387). Academic

Press. https://doi.org/https://doi.org/10.1016/B978-0-12-815554-7.00013-1

Einarsson, R., & Persson, U. M. (2017). Analyzing key constraints to biogas production from crop residues and manure in the EU—A spatially explicit model. *PLOS ONE*, *12*(1), e0171001. https://doi.org/10.1371/journal.pone.0171001

Elliot, M. (2005). *Statistical Disclosure Control* (K. B. T.-E. of S. M. Kempf-Leonard (ed.); pp. 663–670). Elsevier. https://doi.org/https://doi.org/10.1016/B0-12-369398-5/00378-9

Falahi, M., & Avami, A. (2020). Optimization of the municipal solid waste management system using a hybrid life cycle assessment–emergy approach in Tehran. *Journal of Material Cycles and Waste Management*, *22*(1), 133–149. https://doi.org/10.1007/s10163-019-00919-0

Fang, S., Ping, L., Yang, Z., & Mao, J. (2011). A review of different pretreatment techniques for enhancing biogas production. *2011 International Conference on Materials for Renewable Energy & Environment*, *1*, 263–266. https://doi.org/10.1109/ICMREE.2011.5930810

Francini, G., Lombardi, L., Freire, F., Pecorini, I., & Marques, P. (2019). Environmental and Cost Life Cycle Analysis of Different Recovery Processes of Organic Fraction of Municipal Solid Waste and Sewage Sludge. *Waste and Biomass Valorization*, *10*(12), 3613–3634. https://doi.org/10.1007/s12649-019-00687-w

Fu, W. J., Stromberg, A. J., Viele, K., Carroll, R. J., & Wu, G. (2010). Statistics and bioinformatics in nutritional sciences: analysis of complex data in the era of systems biology. *The Journal of Nutritional Biochemistry*, *21*(7), 561–572. https://doi.org/https://doi.org/10.1016/j.jnutbio.2009.11.007

Gao, M., Li, S., Zou, H., Wen, F., Cai, A., Zhu, R., Tian, W., Shi, D., Chai, H., & Gu, L. (2021). Aged landfill leachate enhances anaerobic digestion of waste activated sludge. *Journal of Environmental Management*, *293*, 112853. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.112853

García Álvaro, A., Ruiz Palomar, C., Díaz Villalobos, I., Hermosilla, D., Muñoz, R., & de Godos, I. (2024). Energy Integration of Thermal Pretreatment in Anaerobic Digestion of Wheat Straw. In *Energies* (Vol. 17, Issue 9). https://doi.org/10.3390/en17092030

George, J., Arun, P., & Muraleedharan, C. (2021). Region-specific biomass feedstock selection for gasification using multi-attribute decision-making techniques. *International Journal of Sustainable Engineering*, *14*(5), 1101–1109. https://doi.org/10.1080/19397038.2020.1790058

Gitinavard, H., Shirazi, M. A., & Fazel Zarandi, M. H. (2020). Sustainable feedstocks selection and renewable products allocation: A new hybrid adaptive utility-based consensus model. *Journal of Environmental Management*, *264*, 110428. https://doi.org/https://doi.org/10.1016/j.jenvman.2020.110428

Göktaş, A., & Akkuş, Ö. (2021). Editorial to the special issue: Recent statistical methods for data analysis, applied economics, business & finance. *Journal of Applied Statistics*, *48*(13–15), 2231–2238. https://doi.org/10.1080/02664763.2021.1991180

Goldin, J., Zhu, W., & Sayre, J. W. (1996). A review of the statistical analysis used in papers published in Clinical Radiology and British Journal of Radiology. *Clinical Radiology*, *51*(1), 47–50. https://doi.org/https://doi.org/10.1016/S0009-9260(96)80219-4

Gopal, L. C., Govindarajan, M., Kavipriya, M. R., Mahboob, S., Al-Ghanim, K. A., Virik, P., Ahmed, Z., Al-Mulhm, N., Senthilkumaran, V., & Shankar, V. (2021). Optimization strategies for improved biogas production by recycling of waste through response surface methodology and artificial neural network: Sustainable energy perspective research. *Journal of King Saud University - Science*, *33*(1), 101241. https://doi.org/https://doi.org/10.1016/j.jksus.2020.101241

Guimarães, C. D., Maia, D. R., & Serra, E. G. (2018). Construction of Biodigesters to Optimize the Production of Biogas from Anaerobic Co-Digestion of Food Waste and Sewage. In *Energies* (Vol. 11, Issue 4). https://doi.org/10.3390/en11040870

Hubenov, V., Carcioch, R. A., Ivanova, J., Vasileva, I., Dimitrov, K., Simeonov, I., & Kabaivanova, L. (2020). Biomethane production using ultrasound pre-treated maize stalks with subsequent microalgae cultivation. *Biotechnology & Biotechnological Equipment*, *34*(1), 800–809. https://doi.org/10.1080/13102818.2020.1806108

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x

Issahaku, M., Derkyi, N. S. A., & Kemausuor, F. (2024). A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters. *Heliyon*, *10*(1), e24019. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e24019

Jameel, M. K., Mustafa, M. A., Ahmed, H. S., Mohammed, A. jassim, Ghazy, H., Shakir, M. N., Lawas, A. M., Mohammed, S. khudhur, Idan, A. H., Mahmoud, Z. H., Sayadi, H., & Kianfar, E. (2024). Biogas: Production, properties, applications, economic and challenges: A review. *Results in Chemistry*, *7*, 101549. https://doi.org/https://doi.org/10.1016/j.rechem.2024.101549

Josimović, L., Prvulović, S., Djordjević, L., Bicok, I., Bakator, M., Premčevski, V., Šarenac, U., & Šeljmeši, D. (2024). Enhancing Biogas Plant Efficiency for the Production of Electrical and Thermal Energy. In *Applied Sciences* (Vol.

14, Issue 13). https://doi.org/10.3390/app14135858

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas Production and Applications in the Sustainable Energy Transition. *Journal of Energy*, *2022*(1), 8750221. https://doi.org/https://doi.org/10.1155/2022/8750221

Kainthola, J., Shariq, M., Kalamdhad, A. S., & Goud, V. V. (2021). Comparative study of different thermal pretreatment techniques for accelerated methane production from rice straw. *Biomass Conversion and Biorefinery*, *11*(4), 1145–1154. https://doi.org/10.1007/s13399-019-00537-8

Kalaiselvan, N., Glivin, G., Bakthavatsalam, A. K., Mariappan, V., Premalatha, M., Raveendran, P. S., Jayaraj, S., & Sekhar, S. J. (2022). A waste to energy technology for Enrichment of biomethane generation: A review on operating parameters, types of biodigesters, solar assisted heating systems, socio economic benefits and challenges. *Chemosphere*, *293*, 133486. https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.133486

Karthikeyan, P. K., Bandulasena, H. C. H., & Radu, T. (2024). A comparative analysis of pre-treatment technologies for enhanced biogas production from anaerobic digestion of lignocellulosic waste. *Industrial Crops and Products*, *215*, 118591. https://doi.org/https://doi.org/10.1016/j.indcrop.2024.118591

Keerthana Devi, M., Manikandan, S., Oviyapriya, M., Selvaraj, M., Assiri, M. A., Vickram, S., Subbaiya, R., Karmegam, N., Ravindran, B., Chang, S. W., & Awasthi, M. K. (2022). Recent advances in biogas production using Agro-Industrial Waste: A comprehensive review outlook of Techno-Economic analysis. *Bioresource Technology*, *363*, 127871. https://doi.org/https://doi.org/10.1016/j.biortech.2022.127871

Kelif Ibro, M., Ramayya Ancha, V., & Beyene Lemma, D. (2024). Biogas Production Optimization in the Anaerobic Codigestion Process: A Critical Review on Process Parameters Modeling and Simulation Tools. *Journal of Chemistry*, *2024*(1), 4599371. https://doi.org/https://doi.org/10.1155/2024/4599371

Kenney, K. L., Smith, W. A., Gresham, G. L., & Westover, T. L. (2013). Understanding biomass feedstock variability. *Biofuels*, *4*(1), 111–127. https://doi.org/10.4155/bfs.12.83

Khan, M. U., Usman, M., Ashraf, M. A., Dutta, N., Luo, G., & Zhang, S. (2022). A review of recent advancements in pretreatment techniques of lignocellulosic materials for biogas production: Opportunities and Limitations. *Chemical Engineering Journal Advances*, *10*, 100263. https://doi.org/https://doi.org/10.1016/j.ceja.2022.100263

Khune, S., Otieno, B., Kabuba, J., Ochieng, G., & Osifo, P. (2023). Pilot scale study of anaerobic treatment of food waste using ambient and solar heated digesters. *International Journal of Sustainable Energy*, *42*(1), 1569–1582. https://doi.org/10.1080/14786451.2023.2275818

Kouzi, A. I., Puranen, M., & Kontro, M. H. (2020). Evaluation of the factors limiting biogas production in full-scale processes and increasing the biogas production efficiency. *Environmental Science and Pollution Research*, *27*(22), 28155–28168. https://doi.org/10.1007/s11356-020-09035-1

Kumar, A., Guha, A., & Banerjee, S. (2024). Transforming Simulated Data into Experimental Data Using Deep Learning for Vibration-Based Structural Health Monitoring. In *Machine Learning and Knowledge Extraction* (Vol. 6, Issue 1, pp. 18–40). https://doi.org/10.3390/make6010002

Li, C., Champagne, P., & Anderson, B. C. (2013). Biogas production performance of mesophilic and thermophilic anaerobic co-digestion with fat, oil, and grease in semi-continuous flow digesters: effects of temperature, hydraulic retention time, and organic loading rate. *Environmental Technology*, *34*(13–14), 2125–2133. https://doi.org/10.1080/09593330.2013.824010

Lindkvist, E. (2020). *System studies of biogas production : comparisons and performance*. https://doi.org/10.3384/diss.diva-165274

Massaro, V., Digiesi, S., Mossa, G., & Ranieri, L. (2015). The sustainability of anaerobic digestion plants: a win–win strategy for public and private bodies. *Journal of Cleaner Production*, *104*, 445–459. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.05.021

Menaka, D., Nandhakumar, S., Abishek, R., Raghavendran, M. R., & Hariharan, A. S. V. (2023). Smart Optimization of Biogas Production for Enhanced Gas Yield. *2023 International Conference on Data Science, Agents & Artificial Intelligence (ICDSAAI)*, 1–4. https://doi.org/10.1109/ICDSAAI59313.2023.10452630

Mitraka, G.-C., Kontogiannopoulos, K. N., Batsioula, M., Banias, G. F., Zouboulis, A. I., & Kougias, P. G. (2022). A Comprehensive Review on Pretreatment Methods for Enhanced Biogas Production from Sewage Sludge. In *Energies* (Vol. 15, Issue 18). https://doi.org/10.3390/en15186536

Mohan, S., Barboza, A. B. V, Ashwini, K., & Dinesha, P. (2024). Biogas yield from co-digesting banana pseudostems with cow dung: Transitioning from mesophilic to thermophilic regimes. *Cogent Engineering*, *11*(1), 2429774. https://doi.org/10.1080/23311916.2024.2429774

Montgomery, L., & Bochmann, G. (2014). *Pretreatment of Feedstock for Enhanced Biogas Production*.

Njuguna Matheri, A., Mbohwa, C., Ntuli, F., Belaid, M., Seodigeng, T., Catherine Ngila, J., & Kinuthia Njenga, C. (2018). Waste to energy bio-digester selection and design model for the organic fraction of municipal solid waste. *Renewable and Sustainable Energy Reviews*, *82*, 1113–1121. https://doi.org/https://doi.org/10.1016/j.rser.2017.09.051

Nkemka, V. N., Arenales-Rivera, J., & Murto, M. (2014). Two-Stage Dry Anaerobic Digestion of Beach Cast Seaweed and Its Codigestion with Cow Manure. *Journal of Waste Management*, *2014*(1), 325341. https://doi.org/https://doi.org/10.1155/2014/325341

Nyang'au, J. O., El Mahdi, J., Møller, H. B., & Sørensen, P. (2024). Unlocking higher methane yields and digestate nitrogen availability in soil through thermal treatment of feedstocks in a two-step anaerobic digestion. *Chemical and Biological Technologies in Agriculture*, *11*(1), 186. https://doi.org/10.1186/s40538-024-00694-7

Obileke, K., Makaka, G., Tangwe, S., & Mukumba, P. (2024). Improvement of biogas yields in an anaerobic digestion process via optimization technique. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-04540-6

Obileke, K., Mamphweli, S., Meyer, E. L., Makaka, G., & Nwokolo, N. (2020). Design and Fabrication of a Plastic Biogas Digester for the Production of Biogas from Cow Dung. *Journal of Engineering*, *2020*(1), 1848714. https://doi.org/https://doi.org/10.1155/2020/1848714

Olatunji, K. O., & Madyira, D. M. (2024). Comparative Analysis of the Effects of Five Pretreatment Methods on Morphological and Methane Yield of Groundnut Shells. *Waste and Biomass Valorization*, *15*(1), 469–486. https://doi.org/10.1007/s12649-023-02177-6

Olatunji, K. O., Madyira, D. M., Ahmed, N. A., Jekayinfa, S. O., & Ogunkunle, O. (2022). Modelling the effects of particle size pretreatment method on biogas yield of groundnut shells. *Waste Management & Research*, *40*(8), 1176–1188. https://doi.org/10.1177/0734242X211073852

Olatunji, O. O., Adedeji, P. A., Madushele, N., Rasmeni, Z. Z., & van Rensburg, N. J. (2024). Evolutionary optimization of biogas production from food, fruit, and vegetable (FFV) waste. *Biomass Conversion and Biorefinery*, *14*(11), 12113–12125. https://doi.org/10.1007/s13399-023-04506-0

Otieno, E. O., Kiplimo, R., & Mutwiwa, U. (2023). Optimization of anaerobic digestion parameters for biogas production from pineapple wastes co-digested with livestock wastes. *Heliyon*, *9*(3), e14041. https://doi.org/https://doi.org/10.1016/j.heliyon.2023.e14041

Park, S., Han, S. K., Song, E., Kim, H., Kim, M., & Lee, W. (2020). Effect of hydrothermal pre-treatment on physical properties and co-digestion from food waste and sewage sludge mixture. *Waste Management & Research*, *38*(5), 546–553. https://doi.org/10.1177/0734242X19897123

Pham Van, D., Fujiwara, T., Hoang, M., & Pham Phu, S. T. (2020). Comparison Between Single and Two-Stage Anaerobic Digestion of Vegetable Waste: Kinetics of Methanogenesis and Carbon Flow. *Waste and Biomass Valorization*, *11*. https://doi.org/10.1007/s12649-019-00861-0

Piadeh, F., Offie, I., Behzadian, K., Rizzuto, J. P., Bywater, A., Córdoba-Pachón, J.-R., & Walker, M. (2024). A critical review for the impact of anaerobic digestion on the sustainable development goals. *Journal of Environmental Management*, *349*, 119458. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.119458

Prussi, M., Panoutsou, C., & Chiaramonti, D. (2022). Assessment of the Feedstock Availability for Covering EU Alternative Fuels Demand. In *Applied Sciences* (Vol. 12, Issue 2). https://doi.org/10.3390/app12020740

Ramaraj, R., & Unpaprom, Y. (2016). Effect of temperature on the performance of biogas production from Duckweed. *Chemical Science*, *1*, 58–66.

Ren, Y., Wang, C., He, Z., Qin, Y., & Li, Y.-Y. (2022). Biogas production performance and system stability monitoring in thermophilic anaerobic co-digestion of lipids and food waste. *Bioresource Technology*, *358*, 127432. https://doi.org/https://doi.org/10.1016/j.biortech.2022.127432

Ruiz-Aguilar, G. M. L., Nuñez-Palenius, H. G., Lovanh, N., & Camarena-Martínez, S. (2022). Comparative Study of Methane Production in a One-Stage vs. Two-Stage Anaerobic Digestion Process from Raw Tomato Plant Waste. In *Energies* (Vol. 15, Issue 23). https://doi.org/10.3390/en15239137

Salam, S., Parveen, R., Azad, S. M., & Salam, M. (2020). Understanding the Performance of Domestic Biodigesters in Bangladesh: A Study from Household Level Survey. *Business and Management Studies*, *6*, 27. https://doi.org/10.11114/bms.v6i2.4869

Scherzinger, M., & Kaltschmitt, M. (2021). Thermal pre-treatment options to enhance anaerobic digestibility – A review. *Renewable and Sustainable Energy Reviews*, *137*, 110627. https://doi.org/https://doi.org/10.1016/j.rser.2020.110627

Shaibur, M. R., Husain, H., & Arpon, S. H. (2021). Utilization of cow dung residues of biogas plant for sustainable development of a rural community. *Current Research in Environmental Sustainability*, *3*, 100026. https://doi.org/https://doi.org/10.1016/j.crsust.2021.100026

Sidi Habib, S., Torii, S., S., K. M., & Charivuparampil Achuthan Nair, A. (2024). Optimization of the Factors Affecting Biogas Production Using the Taguchi Design of Experiment Method. In *Biomass* (Vol. 4, Issue 3, pp. 687–703). https://doi.org/10.3390/biomass4030038

Tharmarajah, N., Shahbaz, K., & Baroutian, S. (2024). Textile waste pretreatment for anaerobic digestion: a review and technology feasibility study. *Journal of Chemical Technology & Biotechnology*, *99*(11), 2213–2227. https://doi.org/https://doi.org/10.1002/jctb.7728

Vaneeckhaute, C., Styles, D., Prade, T., Adams, P., Thelin, G., Rodhe, L., Gunnarsson, I., & D'Hertefeldt, T. (2018).

Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: A multi-dimensional sustainability assessment. *Resources, Conservation and Recycling*, *136*, 110–117. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.03.027

Walker, M., Theaker, H., Yaman, R., Poggio, D., Nimmo, W., Bywater, A., Blanch, G., & Pourkashanian, M. (2017). Assessment of micro-scale anaerobic digestion for management of urban organic waste: A case study in London, UK. *Waste Management*, *61*, 258–268. https://doi.org/https://doi.org/10.1016/j.wasman.2017.01.036

Wang, M., Wang, J., Li, Y., Li, Q., Li, P., Luo, L., Zhen, F., Zheng, G., & Sun, Y. (2022). Low-Temperature Pretreatment of Biomass for Enhancing Biogas Production: A Review. In *Fermentation* (Vol. 8, Issue 10). https://doi.org/10.3390/fermentation8100562

Wang, S., Ma, F., Ma, W., Wang, P., Zhao, G., & Lu, X. (2019). Influence of Temperature on Biogas Production Efficiency and Microbial Community in a Two-Phase Anaerobic Digestion System. In *Water* (Vol. 11, Issue 1). https://doi.org/10.3390/w11010133

Welfle, A., & Röder, M. (2022). Mapping the sustainability of bioenergy to maximise benefits, mitigate risks and drive progress toward the Sustainable Development Goals. *Renewable Energy*, *191*, 493–509. https://doi.org/https://doi.org/10.1016/j.renene.2022.03.150

Yadav, P., Yadav, S., Singh, D., Shekher Giri, B., & Mishra, P. K. (2022). Barriers in biogas production from the organic fraction of municipal solid waste: A circular bioeconomy perspective. *Bioresource Technology*, *362*, 127671. https://doi.org/https://doi.org/10.1016/j.biortech.2022.127671

Yalcinkaya, S. (2020). A spatial modeling approach for siting, sizing and economic assessment of centralized biogas plants in organic waste management. *Journal of Cleaner Production*, *255*, 120040. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.120040

Yang, S., Hou, Q., Zhu, M., Liu, Y., & Li, S. (2024). Innovative biogas energy system: Enhancing efficiency and sustainability through multigeneration integration. *Journal of Environmental Management*, *371*, 123118. https://doi.org/https://doi.org/10.1016/j.jenvman.2024.123118

Yong, Z. J., Bashir, M. J. K., & Hassan, M. S. (2021). Biogas and biofertilizer production from organic fraction municipal solid waste for sustainable circular economy and environmental protection in Malaysia. *Science of The Total Environment*, *776*, 145961. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.145961

Yousefi-Nasab, S., Safdari, J., & Karimi-Sabet, J. (2024). A review of experimental and simulation methods for determining accommodation coefficients, particularly TMAC, at fluid-surface interfaces. *Microfluidics and*

Nanofluidics, *28*(8), 54. https://doi.org/10.1007/s10404-024-02747-7

Zheng, X., & Li, R. (2024). Critical Review on Two-Stage Anaerobic Digestion with H2 and CH4 Production from Various Wastes. In *Water* (Vol. 16, Issue 11). https://doi.org/10.3390/w16111608

Zhou, Y., Hu, Y., Chen, A. J. Y., Cheng, Z., Bi, Z., Zhang, R., & Lou, Z. (2022). Environmental impacts and nutrient distribution routes for food waste separated disposal on large-scale anaerobic digestion/ composting plants. *Journal of Environmental Management*, *318*, 115624. https://doi.org/https://doi.org/10.1016/j.jenvman.2022.115624