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Improving biogas yield and environmental performance through waste pre-treatment in anaerobic digestion

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ABSTRACT

Organic waste is both an escalating environmental burden and an underutilized renewable-energy resource, especially in arid, rapidly urbanizing contexts such as Oman. This study evaluates how biodigester performance can be improved through feedstock selection and pre-treatment to increase biogas yield and overall viability. A mixed-methods approach combined laboratory-scale biodigester experiments with simulated scenarios. Five feedstocks (food waste, agricultural residues, livestock manure, mixed organic waste, and food-and-crop waste) and three pre-treatment methods (mechanical, thermal, and chemical) were assessed. Process variables, including pH, temperature, volatile solids reduction, and chemical oxygen demand, were monitored, and regression modeling with ANOVA quantified their influence on biogas yield. Thermal pre-treatment delivered the most substantial gains, increasing biogas yield by 25–30% and raising methane content to ~65%, outperforming mechanical and chemical options. Food waste and food-and-crop waste achieved the highest daily outputs (>58 L/day), while co-digestion enhanced microbial activity and digestion stability. Biodigester deployment can reduce greenhouse gas emissions by up to 70% and divert up to 90% of organic waste from landfills. High-yield systems show payback periods of ~2–2.5 years and net returns exceeding 30%. Statistical results confirm pre-treatment choice and pH as significant predictors of biogas output. During monitoring, reactors operated near 35°C and pH 6.8–7.2, achieving ~35% reduction in volatile solids and a COD of ~27,500 mg/L. Digestate contained ~2.5% N, ~1.2% P, and ~1.8% K for agricultural use. The regression explained 82% of the variance ($R^2 = 0.82$). Overall, the findings support optimized biodigester systems as scalable waste-to-energy solutions.

Keywords: anaerobic digestion, greenhouse gas reduction, renewable energy, environmental engineering, emission mitigation.

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.

Recent research has demonstrated substantial progress in anaerobic digestion (AD) and biodigester performance improvement. Key achievements include (i) co-digestion approaches that balance C/N ratio and improve stability, (ii) pre-treatment techniques (mechanical, thermal, and chemical) that enhance hydrolysis and increase methane potential, (iii) two-stage digestion configurations that separate hydrolysis/acidogenesis from methanogenesis to improve process control, and (iv) the growing use of sensor-based/IoT monitoring to maintain optimal pH–temperature conditions and reduce operational failures. Collectively, these advances indicate that biodigester outputs can be significantly enhanced when feedstock properties, pre-treatment, and operational parameters are optimized in an integrated way.

Recent syntheses also show that the effectiveness of pre-treatment is not uniform across waste types; methane-yield responses can vary substantially depending on substrate composition, treatment severity, and process conditions, thereby strengthening the need for comparative and context-specific optimization studies. In parallel, current AD research increasingly emphasizes integrated decision-making using sensor/IoT monitoring and data-driven models (AI/ML) to improve prediction, control, and scale-up reliability in real operating environments

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 and Wu, 2022) that transform organic waste into energy while minimizing ecological footprints.

Despite these advances, three gaps remain in the current knowledge – especially for arid, rapidly urbanizing contexts such as Oman. First, there is limited comparative evidence using locally relevant feedstocks (e.g., food waste, agricultural residues, manure, and mixed streams) under a consistent experimental and analytical framework, making it difficult to recommend the best feedstock options for Oman. Second, while pre-treatment is known to improve digestibility, there is insufficient clarity on which pre-treatment performs best for specific Omani waste streams and which operating variables most strongly predict biogas yield under mesophilic conditions. Third, many studies report technical performance without linking it to environmental and economic viability (GHG reduction, landfill diversion, payback), which is necessary for adoption decisions aligned with national sustainability targets. Consequently, decision-makers still lack an evidence-based, Oman-relevant "optimization package" that identifies the best feedstock–pre-treatment combination, quantifies key predictors, and demonstrates techno-environmental feasibility.

To address these gaps, 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 emphasizing the core stages of anaerobic digestion (hydrolysis/acidogenesis 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).

Accordingly, the purpose of this study is to develop and validate an Oman-relevant biodigester optimization approach by (i) comparing multiple locally available organic feedstocks, (ii) testing mechanical, thermal, and chemical pre-treatments, and (iii) quantifying how operational parameters (e.g., pH and temperature) and treatment choices influence biogas yield using regression/ANOVA. The expected scientific contribution is a reproducible evidence base that (a) identifies the highest-performing feedstock–pre-treatment combination for improved methane-rich biogas output and (b) establishes the key process predictors that explain performance variability, alongside indicative environmental and economic feasibility for scaling (Amuzu-Sefordzi *et al*., 2018).

Based on prior evidence and the Oman context, the study tests the following hypotheses/expectations:

- H1: Pre-treatment significantly increases biogas yield compared with untreated feedstocks, with thermal pre-treatment producing the largest improvement.
- H2: Food waste and food–crop waste produce higher daily biogas yields and methane content than agricultural residues and manure when operated under comparable conditions.
- H3: pH (near-neutral in methanogenesis) and temperature (mesophilic range) are significant predictors of biogas yield, controlling for feedstock and pre-treatment.
- H4: Co-digestion (mixed streams) improves digestion stability and overall yield relative to single-feedstock digestion.
- H5: The optimized configuration provides improved energy recovery and reduced waste-to-landfill potential, supporting scalability under Oman Vision 2040 priorities.

This study generates the first integrated, side-by-side evidence under a single experimental and analytical framework for major Oman-relevant organic feedstocks subjected to multiple pre-treatment routes, linking process performance (biogas yield and methane concentration) with statistically tested predictors. By doing so, it addresses a key unresolved gap in the literature – namely, the absence of comparative, locally contextualized findings that simultaneously evaluate operational, predictive, and techno-environmental feasibility implications for biodigester deployment.

Global challenges in organic waste management

The rapid growth of urban populations and economic activity has significantly increased the generation of organic waste 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 use of resources (Ayodele *et al.,* 2018). Traditional disposal methods, such as landfilling and open dumping, exacerbate these issues by contributing to greenhouse gas emissions and degrading 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 and Persson, 2017) due to limited awareness of the benefits.

Organic waste in Oman: Current practices and challenges

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

The hot and arid climate in Oman presents unique challenges for organic waste management, as high temperatures accelerate the decomposition process, creating odor and leachate issues (Gao *et al.*, 2021). Additionally, the absence of segregated waste collection systems limits the recovery of organic waste for value-added processes (Bywater *et al.*, 2022). Despite these challenges, Oman holds significant potential for leveraging organic waste as a resource. 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).

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.

BACKGROUND

Biodigester technology: An overview

Anaerobic digestion (AD) converts organic waste into biogas (mainly CH_4 and CO_2) and digestate through microbial activity under oxygen-free conditions. Biodigester performance is primarily governed by feedstock characteristics (e.g., moisture, C/N ratio, biodegradability) and operating conditions such as temperature, pH, and hydraulic retention time (Yadav et al., 2022. Because organic waste streams are often heterogeneous, maintaining stable conditions and improving hydrolysis are central technical challenges in achieving consistent methane-rich biogas yields.

Two-stage biodigester configurations can improve stability and performance by separating hydrolysis/acidogenesis from methanogenesis, enabling better control of pH and retention time across phases (Welfle and Röder, 2022. This separation is particularly relevant for mixed and variable feedstocks, where rapid acid formation can inhibit methanogens in single-stage systems. In arid contexts such as Oman – where waste composition and ambient conditions can vary – two-stage digestion is a promising approach for improving resilience, biogas quality, and overall process efficiency (Walker *et al.,* 2017.

Two-stage biodigester systems: Hydrolysis and methanogenesis

Two-stage biodigester systems separate hydrolysis and methanogenesis into distinct reactors, enabling better control of conditions in each phase (Vaneeckhaute *et al.*, 2018). This separation addresses one of the significant 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 and 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.

Advances in biodigester design and efficiency

Recent advances – such as pre-treatment, improved reactor designs, and real-time monitoring – have enhanced biodigester performance in many settings. However, unresolved issues remain for practical deployment in Oman. First, comparative evidence on locally relevant feedstocks under a consistent analytical framework is limited, making it difficult to select optimal substrates for stable high-yield operation (Piadeh *et al.,* 2024). Second, while mechanical, thermal, and chemical pre-treatments are widely reported, their relative effectiveness can vary by waste type, and the key predictors of yield (e.g., pH stability, temperature sensitivity, solids reduction) are not always quantified in a way that supports decision-making (Issahaku *et al.,* 2024).. Third, studies often report technical gains without connecting them to environmental and economic viability metrics needed for adoption (e.g., landfill diversion, GHG reduction potential, and indicative payback) (de Souza Guimarães and da Silva Maia, 2023). Addressing these unresolved issues requires an integrated evaluation of feedstock–pre-treatment combinations, process monitoring, and predictive modeling of yield drivers (Keerthana Devi *et al.,* 2022).

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:

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).

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.

This research aims to address these pressing issues to optimize biodigester systems for enhanced biogas production from organic waste in Oman, thereby supporting sustainable energy generation and effective waste management. To achieve the aim of enhancing biodigester efficiency for sustainable organic waste management in Oman, the following specific objectives were formulated:

1. Assess different organic feedstocks for their suitability in anaerobic digestion.
2. Evaluate mechanical, thermal, and chemical pre-treatment methods to enhance biogas yield.
3. Design and operate a two-stage biodigester system tailored to Oman's arid conditions.
4. Use IoT-based sensors to monitor key biodigester parameters in real time.
5. Simulate co-digestion and system-optimization scenarios to assess scalability.
6. Analyze environmental and economic impacts, including GHG reduction and ROI.
7. Recommend policy and integration strategies for national waste-to-energy adoption.

Objective and scope of the present study

The objective of this study is to develop and validate an Oman-relevant biodigester optimization approach by jointly evaluating feedstock selection, pre-treatment effects, and key process predictors of biogas yield using experimental monitoring and statistical modeling. Specifically, the study aims to:

1. Compare biogas yield and methane content across locally available feedstocks (including mixed/co-digestion scenarios).
2. Evaluate mechanical, thermal, and chemical pre-treatments for improving biodegradability and gas output.
3. Quantify the influence of operating variables (e.g., pH and temperature) on biogas yield using regression analysis and ANOVA.
4. Provide indicative environmental and economic implications for scalable waste-to-energy adoption in Oman.

MATERIALS AND METHODS

Data provenance and separation of baseline data vs. results. Tables 1–7 present baseline (original) input data and experimental setup information collected prior to the digestion runs (sampling sites and feedstock characterization; pretreatment setpoints; factorial design; and Day-1 operating conditions). These baseline values were measured by the author during sample collection, characterization, and initial reactor loading, and are used to define the experimental inputs and ensure comparability across treatments. New scientific results generated by the present study are reported in the Results section and include treatment-dependent biogas performance outcomes (biogas yield and composition), process stability indicators (pH and temperature), degradation metrics (VS reduction and COD), and inferential/statistical modeling results (ANOVA and regression).

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).

- 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).

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

- Suitability assessment: A comparative analysis (Table 2) of different feedstocks was conducted to evaluate their potential for co-digestion. Feedstocks with complementary properties, such as high nitrogen content paired with high carbon residues, were identified to achieve an optimal C/N ratio of 20–30, ensuring maximum microbial activity and biogas production (Dubois *et al.,* 2019).

Table 2 summarizes key parameters, including 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 requires pairing with high-carbon residues such as 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.

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.

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).

Evaluation of effectiveness

The effectiveness of each pre-treatment method was assessed by measuring changes in VS reduction, COD, and biogas yield in small-scale batch tests (Table 4).

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. VS reduction (%) indicates improvement in organic matter degradation potential after pre-treatment (higher reduction = better biodegradability).

- Soluble COD increase (%) reflects increased solubility/availability of organics for microbial action after pre-treatment.
- Biogas yield increase (%) is the percent improvement relative to the untreated control under comparable conditions.
- Values are reported as ranges observed across the batch tests; if replicates (n) were used, report n in the caption (n=3).

Process flow diagram

A flow diagram can illustrate the steps involved in pre-treatment and their integration into the bio digestion process.

Table 2. Chemical properties and suitability assessment of feedstocks

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)

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 the degradation of fibrous materials.

Feedstock Collection → 2. Pre-Treatment (Mechanical/Thermal/Chemical) → 3. Hydrolysis Reactor → 4. Methanogenesis Reactor → 5. Biogas Production

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 scope of the experiments. 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 anaerobic digestion models 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).

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).

This study employed a full-factorial experimental design to evaluate the effects of feedstock type and pre-treatment method on biogas performance in a two-stage biodigester (hydrolysis followed by methanogenesis). Table 5 summarizes the experimental design used to evaluate the effects of feedstock type and pre-treatment method on the performance of two-stage anaerobic digestion (hydrolysis followed by methanogenesis).

Table 4. Summary of pre-treatment conditions and effectiveness indicators (batch tests)

Pre-treatment method	Key condition used in this study	Primary target feedstocks	VS reduction (%)	Soluble COD increase (%)	Biogas yield increase (%)	Main rationale/mechanism
Mechanical (size reduction)	Shredding (particle size reduction)	All feedstocks	20–30	15–20	10–15	Increases surface area and improves microbial access during hydrolysis
Thermal	Heating at 70 °C for 1 hour	All feedstocks	40–50	25–30	25–30	Breaks down complex organics, increases solubilization, and reduces pathogen load
Chemical (alkaline)	NaOH alkaline treatment (see Section 2.3.4 for dose/contact time)	Mainly lignocellulosic residues (e.g., agricultural residues)	35–45	20–25	20–25	Disrupts lignocellulosic structure and improves biodegradability of fibrous materials

After collection (Table 1), each feedstock was homogenized and sub-sampled for baseline characterization prior to any pre-treatment. Baseline properties measured for each feedstock are summarized in Table 1 and were used to assess suitability for digestion and co-digestion.

Accordingly, factorial outcomes are summarized by feedstock and pre-treatment groups using key performance indicators, including daily biogas yield, methane concentration, and organic matter removal (VS reduction and COD). Over the 30-day monitoring period, biogas production averaged 48.13 ± 3.75 L/day (range 41.2–56.4 L/day) and methane content averaged 59.5 ± 1.5% (range 56.6–61.5%), with pH maintained near neutral (6.9–7.1) under mesophilic conditions (~35 °C) and VS reduction averaging 29.8 ± 4.0% (range 23.7–35.9%) as reported in Table 6. COD values averaged 27,502 ± 398 mg/L over the monitoring period, ranging from 26,892 to 28,198 mg/L, indicating consistent handling of organic load and biodegradation performance.

Time-series monitoring (Day 1–30) is presented separately to demonstrate operational stability and daily process dynamics (Table 6).

Baseline reactor conditions were documented on Day 1 to confirm stable mesophilic operation and to establish reference values prior to observing time-dependent changes. The recorded measurements are presented in Table 7.

Pre-treatment protocols: To enhance biodegradability and improve biogas yield, three pre-treatment methods were applied prior to feeding the hydrolysis reactor: mechanical size reduction, thermal treatment (70 °C for 1 hour), and alkaline chemical treatment using NaOH (applied primarily to lignocellulosic agricultural residues).

All treatments followed standardized handling and documentation steps to ensure comparability across feedstocks and a clear linkage between Methods and Results.

Preparation steps

1. Sorting and homogenization: Each feedstock was manually sorted to remove

Table 5. Experimental design matrix

Factor	Levels/description	How it is reported in results
Feedstocks (5)	F1 Food waste; F2 Agricultural residues; F3 Livestock manure; F4 Mixed organic waste; F5 Food-and-crop waste	Separate results by F1–F5
Pre-treatment (4)	P0 Control (none); P1 Mechanical; P2 Thermal (70 °C for 1 hour); P3 Chemical (alkaline NaOH, primarily for lignocellulosic residues)	Compare P0–P3 within each feedstock
Digestion configuration	Two-stage: Stage 1 Hydrolysis → Stage 2 Methanogenesis	Stage-wise outputs + overall
Replicates	n = 3 independent replicates per (Fi × Pj)	Mean ± SD; ANOVA uses n
Controls	P0 untreated is the internal control; blank (inoculum only): not used	Blank gas subtracted: No
Total runs	5 × 4 × 3 = 60 runs	State final number explicitly: Total runs = 60

Table 6. Sampling locations and physicochemical properties of the five organic feedstocks (F1–F5) in Oman (TS/VS/ash, pH, C/N), with co-digestion suitability.

Feedstock ID	Feedstock type	Location	Source	Latitude	Longi-tude	Sample mass (kg)	Moisture (%)	TS (%)	VS (% of TS)	Ash/fixed solids (% of TS)*	pH	C/N ratio	Suitability for co-di-gestion
F1	Food waste	Muscat	Urban house-holds	23.588	58.3829	50	75	25	85	15	5.5	18	High (Pair with high-C residues)
F2	Agricultur-al residues	Salalah	Agri-cultural farms	17.0198	54.089	60	20	80	60	40	6.8	40	High (Pair with high-N residues)
F3	Livestock manure	Sohar	Live-stock farms	24.3643	56.7075	55	65	35	55	45	7.2	15	Medium (Comple-mentary with crop waste)
F4	Mixed organic waste	Nizwa	Urban & rural collec-tion	22.9333	57.5333	70	60	40	65	35	6	25	High (Ba-lanced composi-tion)
F5	Food and crop waste	Sur	Urban mar-kets & farms	22.5667	59.5289	65	50	30	70	30	6.5	22	High (Ready for co-diges-tion)

Note: *Ash/Fixed solids calculated as 100 − VS (% of TS) using Table 2 values.

Table 7. Initial reactor operating conditions (Day 1, as loaded)

Parameter	Value (Day 1)
pH	7
Temperature (°C)	35
COD (mg/L)	27,877
VS reduction (%)	34.7

non-biodegradable contaminants (e.g., plastics, stones, metals) and homogenized by thorough mixing to reduce within-sample variability.

2. Sub-sample allocation: The homogenized material was divided into equal sub-samples corresponding to each treatment condition (control, mechanical, thermal, chemical). The wet mass of each sub-sample was recorded using a balance.
3. Baseline measurements: For each sub-sample, initial pH was measured using a calibrated pH meter. Total solids (TS) and volatile solids (VS) were determined using standard gravimetric methods (report the standard used, e.g., APHA).
4. Standardization of substrate loading: To ensure fair comparison between treatments, the wet mass used per run was adjusted to provide a similar TS input across treatments. The volume of dilution water added (if any) was recorded.
5. Post-treatment checks: After each pre-treatment, the substrate was cooled/returned to ambient temperature (if heated), and pH was measured again before feeding into the reactor.

Mechanical pre-treatment (particle size reduction)

Mechanical pre-treatment was performed to increase surface area and accelerate hydrolysis.

Protocol:

1. Equipment: A laboratory shredder/grinder was used (state make/model and power rating, if available).
2. Target particle size: Substrate was shredded and screened to achieve a target particle size of 5–10 mm (report the screen size used).
3. Processing duration: Each batch was processed for a fixed duration (e.g., 2–5 minutes) or until the target size distribution was achieved.
4. Mixing: The shredded material was mixed thoroughly for uniformity (e.g., 2 minutes of manual mixing).
5. Handling and storage: The treated substrate was transferred to sealed containers and used promptly for reactor feeding; if storage was necessary, it was kept at 4 °C and used within 24 hours.

Thermal pre-treatment (70 °C for 1 hour)

Thermal pre-treatment was conducted at 70 °C for 60 minutes to improve the solubilization of organics and enhance subsequent methane production.

Protocol:

1. Batch preparation: A known wet mass of substrate was placed into heat-resistant containers

(glass or stainless steel). Containers were sealed to minimize moisture loss.
2. Heating: Containers were heated in a thermostatic water bath or oven set to 70 °C (±1 °C) for 60 minutes. Temperature was verified using an independent probe/thermometer.
3. Intermittent agitation (recommended): Containers were gently agitated every 10–15 minutes to ensure uniform heating (state whether agitation was performed).
4. Cooling: After heating, containers were cooled to room temperature (25–30 °C) using ambient cooling or a water bath; cooling time was recorded.
5. Post-treatment measurements: pH was re-measured, and the treated substrate was fed into the hydrolysis reactor immediately or stored at 4 °C and used within 24 hours.

Chemical (alkaline) pre-treatment using NaOH

Alkaline pre-treatment was applied using sodium hydroxide (NaOH) to facilitate breakdown of lignocellulosic fractions and increase substrate accessibility, particularly for agricultural residues.

Protocol:
1. NaOH solution preparation: A fresh NaOH solution was prepared at a defined concentration (e.g., 1–2% w/v or 0.5–1.0 M; report the exact concentration used).
2. Dose definition: NaOH dosage was specified on a TS basis as D (g NaOH/kg TS). The required mass of NaOH was calculated from the batch TS. (Example reporting: “NaOH was applied at 20 g/kg TS.”)
3. Application and mixing: The calculated NaOH solution volume was added to the substrate and mixed to form a uniform slurry (e.g., 10 minutes at a fixed mixing speed, or standardized manual mixing).
4. Contact time: The slurry was held in sealed containers for a fixed contact period (e.g., 12–24 hours) at ambient temperature (or controlled temperature, if used).
5. Neutralization prior to digestion: After contact time, the treated slurry was neutralized to pH 6.8–7.2 using dilute acid (e.g., HCl) or buffer before feeding to prevent inhibition of methanogens. Final pH was confirmed using a calibrated meter.
6. Safety: NaOH handling was performed with gloves, goggles, and lab coat; spills and wastes were managed according to institutional laboratory safety procedures.

Documentation and traceability

For each treated batch, the following were recorded: feedstock type, wet mass, TS/VS (where measured), treatment condition (control/mechanical/thermal/chemical), key setpoints (particle size, temperature–time profile, NaOH concentration/dose/contact time), pH before and after treatment, and time between treatment completion and reactor feeding. This documentation ensures reproducibility and supports a clear, logical progression from Methods to Results.

Reactor setup and instrumentation

The biodigester was configured as a two-stage system to separate hydrolysis/acidogenesis from methanogenesis, improving process control and stability.

Stage 1 (Hydrolysis reactor) had a 50-L capacity and was operated under slightly acidic conditions (pH 5.5–6.5) with a retention time of 3–5 days, while Stage 2 (Methanogenesis reactor) had a 100-L capacity and was maintained at near-neutral pH (6.8–7.2) with a retention time of 15–20 days. Both reactors were constructed from stainless steel and insulated to support stable operation. A mechanical mixing system (stirrers/agitator) was used to improve uniformity and prevent sedimentation during digestion.

Operationally, the system was run under mesophilic conditions (35 °C ± 2 °C) with a total hydraulic retention time (HRT) of 20–25 days, and mixing was applied to maintain uniform microbial distribution. A schematic representation of the two-stage configuration is provided in Figure 1.

Process monitoring instruments used to obtain experimental parameters: (a) inline gas flow meter for daily biogas volume (L/day); (b) portable gas analyzer/GC sampling line for CH_4/CO_2; (c) calibrated pH meter for slurry/effluent pH; (d) temperature probe for mesophilic control. Readings from these instruments generated the parameters reported in Tables 8–9.

Instrumentation and measurement points

The biodigester was equipped for continuous/regular monitoring of process parameters and output quality. IoT-enabled sensors were used to

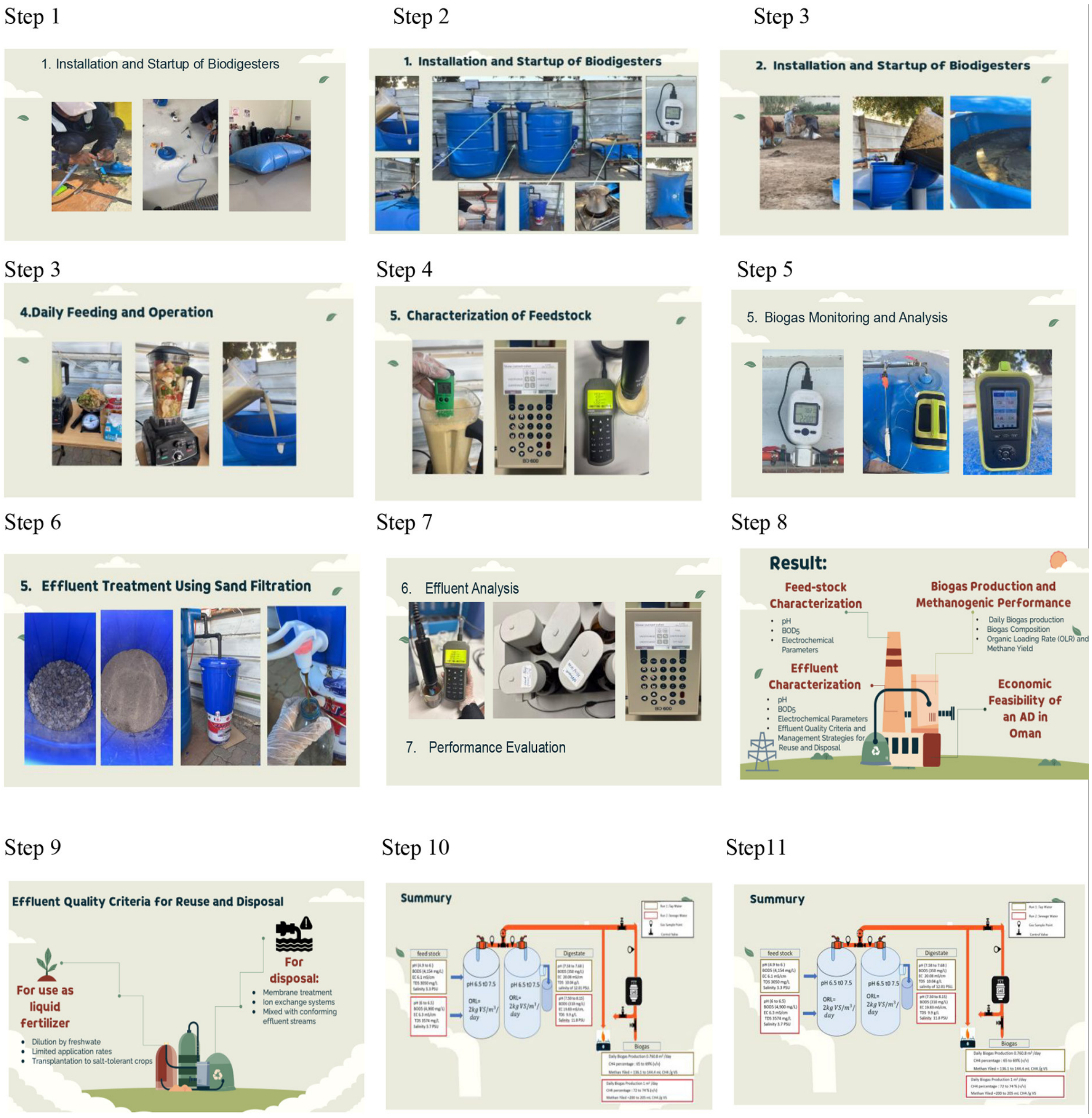

Figure 1. Photographs of the two-stage biodigester system used in this study

monitor temperature, pH, gas production, and feedstock levels in real time (where applicable). Biogas volume was quantified using a gas flow meter, and biogas composition (methane, CO_2 and trace gases) was analyzed using gas chromatography. Process monitoring included pH, temperature, COD, and VS reduction, measured using standard analytical instruments/methods. The full set of parameters and analytical methods is summarized in Table 5 (e.g., pH meter, temperature probe, spectrophotometry for COD, gravimetric analysis for VS reduction, AAS for heavy metals).

Sensor details, calibration, and data logging

To ensure reproducibility, report the exact sensor/instrument model and calibration routine as follows (replace the bracketed fields with your actual lab details):

1. pH measurement – portable benchtop pH meter (Model/Brand: Hanna Instruments HI 2211) with combination pH electrode (HI 1131). Calibrated using standard buffer solutions (pH 4.00, 7.00, and 10.00) before each sampling day (two-point minimum; three-point when drift exceeded ±0.05 pH units).
2. Temperature – digital thermometer with probe (Model/Brand: Testo 110 with Pt100 probe). Verified against a reference thermometer weekly and checked at the operating setpoint (35 °C ± 2 °C).
3. Gas flow meter – Wet gas meter for biogas volume measurement (Model/Brand: Ritter

Drum-type Gas Meter (e.g., TG series)). A daily zero-check and leak test were performed, and all tubing connections were inspected for leaks before recording biogas volumes.

4. Gas chromatography – gas chromatograph (Model/Brand: Agilent 7890B) equipped with a thermal conductivity detector (TCD) and packed column (HayeSep Q / Porapak Q, stainless steel, 2 m × 1/8 in; carrier gas: N_2). Calibrated using certified CH_4/CO_2 standard gas mixtures at the start of each batch and verified with a mid-point check standard every sampling day.

Quality assurance and measurement reliability

To ensure data quality, comparability across treatments, and reproducibility of findings, quality assurance/quality control (QA/QC) procedures were applied across sampling, instrumentation, laboratory analyses, and data handling. All experimental conditions were standardized across the factorial design (feedstock × pre-treatment), and results were summarized from independent replicates (n = 3 per condition) and reported as mean ± SD.

Instrument calibration and verification

All sensors and analytical instruments were calibrated using manufacturer-recommended procedures and verified at regular intervals. pH meters were calibrated using certified buffer solutions (pH 4.0, 7.0, 10.0) prior to sampling; temperature probes were checked against a reference thermometer at the operating setpoint; gas-volume measurement systems were inspected for leaks and subjected to routine zero/accuracy checks; and gas chromatography (GC) was calibrated using certified CH_4/CO_2 standards with periodic mid-point verification checks to confirm stability.

Analytical QA/QC for physicochemical measures

Standard methods were used for TS/VS, COD, and digestate nutrient analyses (e.g., APHA-based protocols as stated in the Methods). For each sampling day, duplicate measurements were performed for key parameters (pH, COD, TS/VS) on a subset of samples, and results were accepted when duplicate values fell within a predefined tolerance (e.g., ≤5% relative difference for COD; ≤0.05 pH units for pH). Where nutrient or elemental testing was conducted (e.g., AAS), calibration curves and check standards were used to confirm analytical accuracy, and any batch failing acceptance criteria was re-run.

Process controls and consistency checks

Standardized feedstock handling (sorting, homogenization, equal sub-sample allocation, and consistent loading on a TS basis) was followed to reduce within-sample variability and ensure comparability across treatment conditions. Treatment setpoints (particle size, temperature–time profile, NaOH concentration/dose/contact time) and pre-/post-treatment pH were recorded for every batch to maintain traceability from Methods to Results.

Reliability metrics and outlier handling

Measurement reliability was evaluated using variability indicators across replicates (e.g., standard deviation and coefficient of variation). Outliers were screened using objective rules (e.g., instrument fault flags, failed calibration checks, or clear recording errors). Values were not removed solely for being extreme; exclusions (if any) were only made when an identifiable methodological cause was documented (e.g., sensor drift, leak detected, GC calibration failure), and the reason was recorded in the lab log.

Data integrity and documentation. All raw readings (sensor logs and laboratory outputs) were stored with timestamps and linked to treatment identifiers (Fi × Pj), ensuring complete traceability for each run. This QA/QC framework supports the reliability of the reported comparisons between feedstocks, pre-treatment methods, and operating predictors of biogas performance.

Operational parameters

- Temperature – yhe 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).

RESULTS AND DISCUSSION

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.

Accordingly, factorial outcomes are summarized by feedstock (F1–F5) × pre-treatment (P0–P3) groups using key performance indicators, including daily and cumulative biogas yield, methane concentration, and organic matter removal (VS reduction and COD). Results are reported as mean ± SD across independent replicates (n = 3 per Fi × Pj), and group differences are tested using ANOVA, with predictor effects further examined using regression modeling. In parallel, time-series monitoring (Day 1–30) is presented separately to demonstrate operational stability (pH, temperature) and daily process dynamics during continuous operation.

Experimental data were collected at regular intervals (Table 6) 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, CO_2, 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. Figure 2 represents a two-stage biodigester system in which organic waste undergoes a series of processes to produce biogas and digestate.

Stage 1: Hydrolysis reactor
- Input: Pre-treated organic waste
- Process: Breakdown of complex organic molecules into simpler compounds.

Stage 2: Methanogenesis reactor
- Input: Hydrolyzed organic matter
- Process: Conversion of intermediate compounds into methane and carbon dioxide.

Biogas storage tank
- Captures and stores biogas for energy utilization.

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

Table 8 summarizes the measurement plan and instrumentation used in the study, showing what was monitored for (i) biogas performance (daily gas volume and composition via flow meter and gas chromatography), (ii) digestate quality and safety (NPK nutrients using APHA chemical methods and heavy metals via AAS), and (iii) process stability and degradation efficiency (pH, temperature, COD by spectrophotometry, and VS reduction by gravimetric analysis). It clarifies how each parameter supports evaluating energy yield, operational control, and fertilizer suitability of the biodigester outputs.

Biogas volumes reported in Table 9 are not blank-corrected, as an inoculum-only (blank) reactor was not included in the experimental run.

Table 9 provides a comprehensive overview of the biodigester's performance over 30

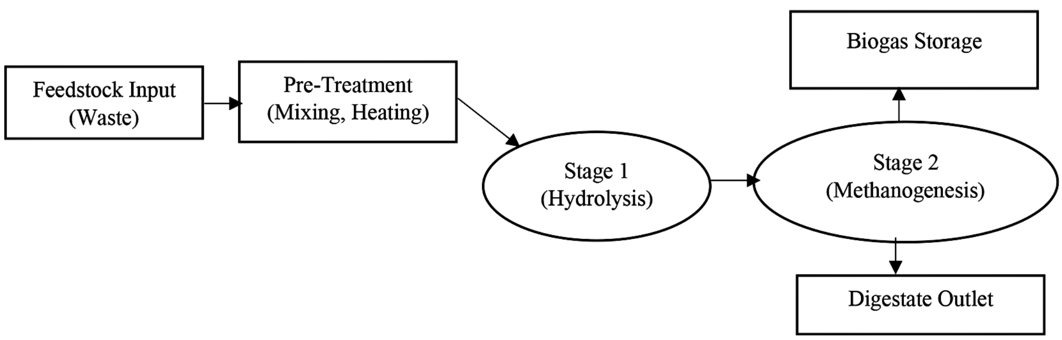

Figure 2. Two-stage biodigester system

Table 8. 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

days. Biogas production demonstrated consistent daily volumes, averaging around 52.5 liters, with minor fluctuations indicating stable feedstock digestion and efficient operation (Aridi and Yehya, 2024). Methane content in the biogas remained stable at 59–61%, indicating 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).

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 (Table 10). 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).

Regression model

$$Y_{biogas} = \beta_0 + \beta_1 X_{feedstock\ type} + + \beta_2 X_{pre\text{-}treatment\ method} + \beta_3 X_{temperature} + \beta_4 X_{pH} + \epsilon \quad (1)$$

Table 9. 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

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 11).

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 11). 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 and Akkuş, 2021).

The F-statistic of 28.35, with a p-value less than 0.001, shows that the regression model as a whole is statistically significant, meaning the predictors collectively have a strong association with biogas yield. Among the individual predictors, temperature (p=1.75, p<0.001β=1.75, p<0.001) and pre-treatment method (p=3.80, p=0.005β=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 increase the average yield by 3.80 L/day. The 95% confidence intervals for

Table 10. 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)

Table 11. 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)

these predictors indicate high precision in their estimates, enhancing the model's reliability.

Table 12 provides 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 and 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 feedstock conversion efficiency 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).

Figure 4 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

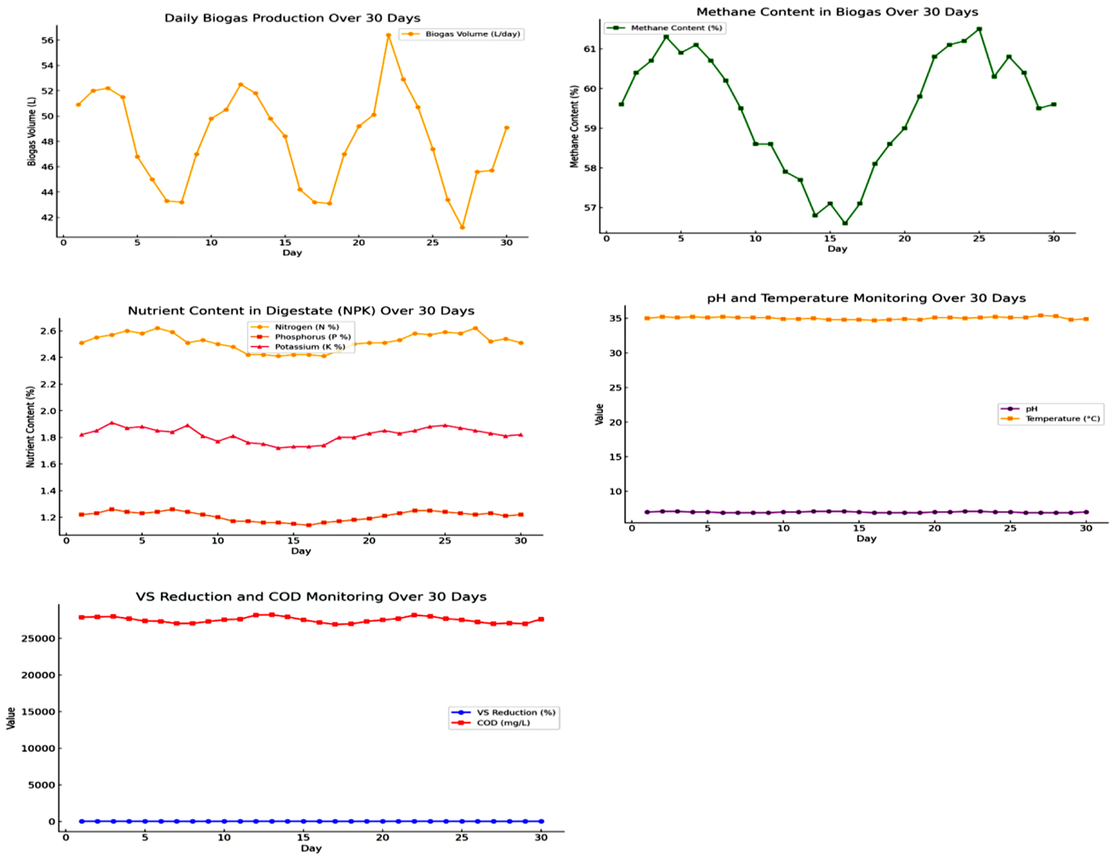

Figure 3. Overview of the biodigester's performanceAlthough feedstock type showed marginal significance (p=0.067), it still contributed to the overall explanatory power of the model, suggesting that variations in feedstock type may influence biogas yield and warrant further investigation. The model fit 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 (Figure 3).

Table 12. 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			

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.

In the Figure 5 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 13). Mechanical, thermal, and chemical, and statistical measures were calculated, including:

- Mean biogas yield – the average yield across all samples for each pre-treatment.

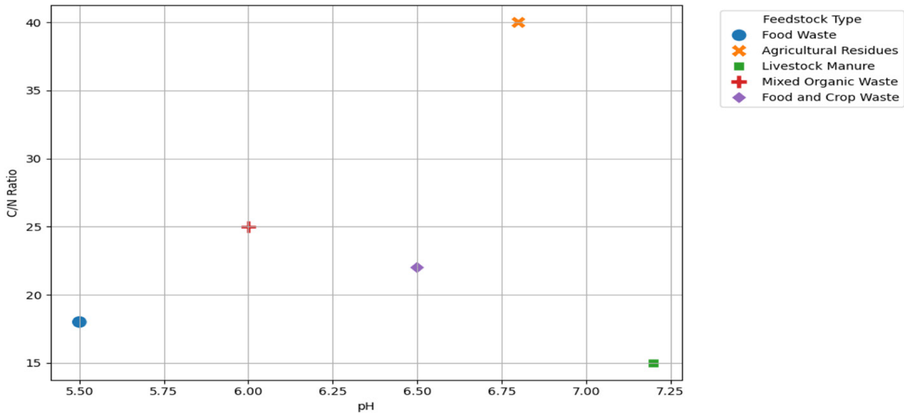

Figure 4. Relationship between pH and the carbon-to-nitrogen (C/N) ratio for different feedstock types

- 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.

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 Figure 6 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 (Olatunji *et al*., 2022).

Thermal pre-treatment yields the highest mean biogas yield with minimal variability, underscoring its effectiveness in 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

Table 13. 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

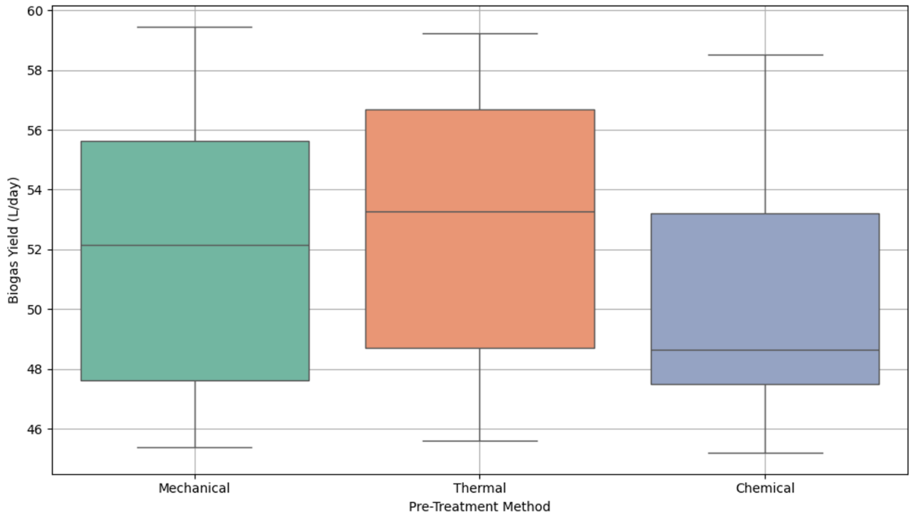

Figure 5. Biogas yield pre-treatment methods

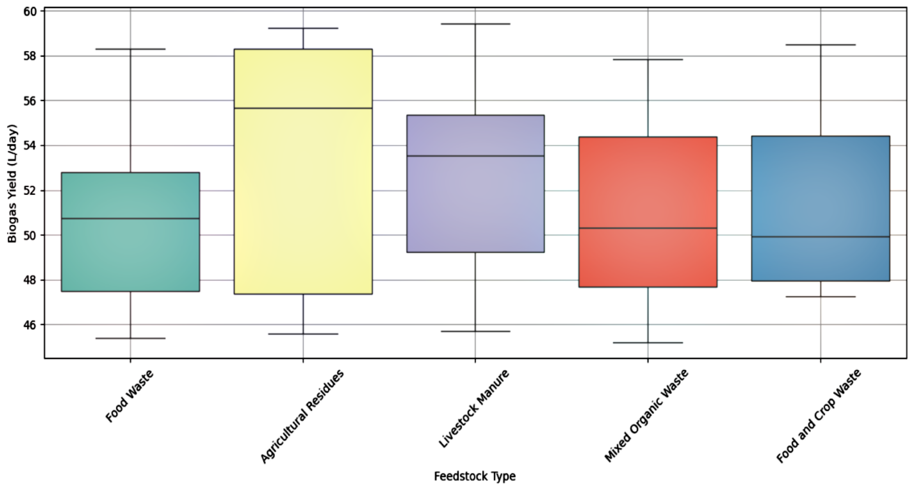

Figure 6. Biogas yield by feedstock types

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 (Olatunji and 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 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 and 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).

Optimization strategies

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. 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).

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. 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.

Real-time monitoring and control systems

The incorporation of real-time monitoring and control systems is critical for optimizing biodigester performance. 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).

Energy recovery and digestate utilization

Maximizing energy recovery from biogas involves refining and upgrading methane content for use as a renewable energy source in power generation, transportation, or as a substitute for natural gas. 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 (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.

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 reduced water use (Menaka *et al.,* 2023). Real-time monitoring systems, particularly those that incorporate IoT and predictive maintenance, have 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 bio-fertilizers, 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.

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 (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 and 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 biodegradability of the feedstock. 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 their high C/N ratio and structural complexity.

The environmental benefits of these systems are evident in the significant reduction of greenhouse gas emissions and high waste diversion rates. Food waste 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 their less favorable characteristics.

Economically, food waste proved to be the most viable feedstock, with a payback period of only 2 years and a net economic return of 35%. Food and crop waste also performed well, with a payback period of 2.5 years and a 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 and 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.

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 existing waste management systems, and the potential to replicate the model across different regions.

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.

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.

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 in rural areas and large-scale units in industrial zones can help ensure widespread adoption. Furthermore, the replication potential extends to other GCC countries, 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.

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.

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.

Socio-economic and cultural factors

Socio-economic and cultural factors also influence the adoption of biodigester systems. 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 lead to resistance to the use of digestate as a fertilizer. Addressing these socio-economic barriers requires targeted education campaigns, financial incentives (Chiu and Lo, 2016), and collaborative engagement with communities and stakeholders to build trust and support.

Managerial and policy implications

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.

Promoting the use of digestate as an organic fertilizer can reduce dependency on chemical fertilizers, improve soil health, and support more 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.

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.

CONCLUSIONS

This study evaluated and optimized biodigester performance for Oman's organic waste streams by examining how feedstock selection, pre-treatment options, and operating variables influence biogas output and sustainability outcomes. The study achieved this goal by integrating experimental findings with scenario-based analysis to provide a coherent basis for performance improvement and sustainability-oriented decision-making in an arid-climate context.

The new scientific results of this study are: (i) thermal pre-treatment delivered the most consistent performance improvement, increasing biogas yield by approximately 25–30% and raising methane content to about 65% compared with mechanical and chemical alternatives; (ii) regression and ANOVA results identified pre-treatment choice and pH as statistically significant predictors of biogas yield, with strong explanatory power ($R^2 \approx 0.82$); and (iii) integrated sustainability evaluation indicates that optimized biodigester deployment can reduce greenhouse gas emissions by up to ~70%, divert up to ~90% of organic waste from landfill, and achieve ~2–2.5 years payback for high-yield feedstocks.

This work fills a key research gap because prior studies often examine feedstock effects, pre-treatment effects, or sustainability outcomes in isolation, even though pre-treatment benefits are highly substrate-dependent and context-sensitive. By providing an integrated comparative assessment across multiple feedstocks and pre-treatment approaches – combined with statistical inference and sustainability indicators – this study strengthens the evidence base for biodigester optimization in Oman and similar environments.

The study also opens clear prospects for scale-up and further research. The results support the selection of suitable pre-treatment strategies and monitoring targets (notably pH) and motivate future work using sensor-enabled monitoring and data-driven optimization for operational stability. Because some outcomes were derived from simulated scenarios, field-scale validation under varying operational and climatic conditions is recommended to confirm real-world performance and improve generalizability

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