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Experimental Evaluation of a Pilot-Scale Anaerobic Digestion System for Kitchen Waste Management at UTAS Al Mussanah, Oman

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ABSTRACT

This study presents an experimental investigation of a 1 m³ floating-drum anaerobic digester for treating fruit and vegetable waste at the University of Technology and Applied Sciences (UTAS), Al Mussanah, Oman. The digester was designed to process approximately 3 kg of organic waste per day, with the substrate prepared at a waste-to-water ratio of 1:1. Operating conditions and biogas production were monitored under naturally varying outdoor conditions from January to October 2024. June was designated as a preparation period for the subsequent operating cycle and was therefore excluded from the monthly performance comparison. The mean digester temperature increased from 29.43 °C during January–May to 35.50 °C during July–October. Correspondingly, the calculated mean methane production increased from 99.82 to 130.96 L/day, representing an increase of approximately 31.2%, with the highest reported production of 144.00 L/day recorded in September. The digester maintained relatively stable pH conditions, ranging from 7.05 to 7.24, with an overall mean of approximately 7.15. Meanwhile, the mean hydrogen sulphide concentration increased from 581.97 to 692.20 ppmv, whereas the reported carbon dioxide concentration decreased from 37.95% to 35.98% between the two monitoring periods. These findings indicate seasonal variations in methane production and biogas composition under the prevailing environmental conditions. However, the field-based experimental design does not establish a direct causal relationship between temperature and methane production. Furthermore, the absence of data on feedstock solids content, normalised methane yield, organic loading rate, hydraulic retention time, and measurement uncertainty limits the assessment of conversion efficiency and commercial feasibility. Overall, this study provides a site-specific, pilot-scale evaluation of anaerobic digestion for organic waste management in Oman and highlights the additional operational and performance measurements required to support a more comprehensive assessment of system efficiency, reliability, and practical applicability.

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1. Introduction

The increasing generation of kitchen and food waste presents significant challenges for sustainable waste management and resource recovery. Conventional disposal practices, particularly landfilling, can lead to the loss of recoverable organic resources and contribute to greenhouse gas emissions. Anaerobic digestion (AD) offers a sustainable alternative by converting biodegradable organic materials into biogas under oxygen-free conditions while producing digestate that may be suitable for beneficial applications following appropriate evaluation [1–3]. Biogas typically consists primarily of methane and carbon dioxide, along with other constituents whose concentrations depend on feedstock characteristics and operating conditions. Food waste contains substantial amounts of biodegradable organic matter, making it a promising substrate for renewable energy recovery through anaerobic digestion. Feedstock characteristics, including moisture content, volatile solids content, carbon-to-nitrogen ratio, and biodegradability, play important roles in determining methane production potential. Previous research has characterized food waste as a suitable substrate for anaerobic digestion and demonstrated its potential for methane generation [4].

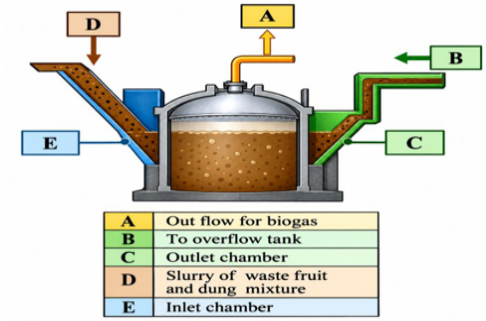


Fig. 1. Schematic representation of an anaerobic biogas plant

Co-digestion studies have demonstrated that combining food waste with animal manure can influence nutrient balance, buffering capacity, and methane production [5–6]. Anaerobic digester performance is also influenced by several operational parameters, including temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT), substrate composition, and reactor configuration [7–13]. Excessive organic loading and the accumulation of volatile fatty acids, particularly under insufficient buffering conditions, can destabilize methanogenic activity and reduce biogas production. Although various anaerobic digestion configurations, including wet digestion, dry digestion, co-digestion, and multi-stage treatment, have been investigated, translating laboratory-scale findings into decentralized applications requires careful consideration of reactor construction, feedstock handling, gas collection, operational reliability, and maintenance requirements [14–15].

Pilot-scale field investigations are therefore essential for evaluating the performance of integrated anaerobic digestion systems under practical operating conditions. Accordingly, this study evaluates a pilot-scale kitchen-waste-to-biogas system installed at the University of Technology and Applied Sciences (UTAS), Al Mussanah, Oman. The investigation focuses on the system configuration, operational characteristics, methane production, and biogas composition under naturally varying outdoor environmental conditions. The findings provide a site-specific assessment of the system's operational performance and potential applicability for decentralized organic waste management. However, the available dataset is insufficient to support a comprehensive evaluation of conversion efficiency or commercial feasibility.

2. Literature Review

Food-waste anaerobic digestion has received considerable attention due to its potential to address organic waste management challenges while recovering renewable energy. Several studies have investigated the dry anaerobic digestion of food waste under mesophilic conditions [2]. Experimental investigations involving different types of food waste have reported methane yields of 348 and 435 mL/g VS after 10 and 28 days, respectively, under the tested conditions. Other studies have examined the co-digestion of dairy manure and food waste, highlighting the importance of substrate combinations in influencing methane production and digestion kinetics. The potential benefits of co-digesting food waste with cattle manure have also been investigated [4–6]. Furthermore, research has explored methane production from potato peels, focusing on the effects of substrate-to-inoculum ratio, pretreatment methods, and co-digestion strategies [1]. Collectively, these findings demonstrate that feedstock characteristics and substrate combinations are important considerations in the design and optimization of anaerobic digestion systems.

Operational stability is another critical factor influencing anaerobic digestion performance. Reviews of food-waste anaerobic digestion have identified process monitoring, microbial management, and operational control as essential considerations for maintaining stable digestion conditions [8–9]. Major challenges include micronutrient deficiencies, foaming, reactor design limitations, and the selection of suitable co-substrates. Previous research has also reviewed developments in pretreatment technologies, co-digestion strategies, and process optimization, emphasizing the influence of feedstock composition and operating conditions on anaerobic bioconversion efficiency [11]. In addition, the effects of additives and microbial community characteristics on process stability and methane production have been investigated [12–13].

At the pilot scale, a study investigated food-waste anaerobic digestion integrated with an outdoor algal–bacterial biogas upgrading system and reported an average biogas production of 68 ± 8 L/day under the investigated operating conditions [14]. Additional studies have addressed food-waste characterization, environmental performance, waste-to-energy conversion pathways, and the selection of appropriate anaerobic digestion technologies [16–21]. Researchers have also evaluated advanced liquefaction–anaerobic digestion processes at laboratory and pilot scales [22–25]. These investigations have contributed valuable insights into digestion kinetics, feedstock characteristics, microbial activity, and process stability [26–29]. However, the reported performance of anaerobic digestion systems cannot be directly generalized across different reactor configurations because of variations in feedstock composition, reactor geometry, organic loading rate, operating temperature, and system complexity.

Despite these advances, further field-based investigations are needed to assess the performance of decentralized anaerobic digestion systems under locally prevailing environmental and operational conditions. The present study addresses this need by evaluating a pilot-scale anaerobic digester utilizing locally available fruit and vegetable waste under the naturally varying outdoor climatic conditions of Al Mussanah, Oman. Related investigations have also examined organic waste composting, fruit and vegetable waste characterization, and biogas production from various organic substrates [30–34]. Building upon these findings, the present study provides a site-specific assessment of anaerobic digestion performance, focusing on operational conditions, methane production, and biogas composition to support the development of decentralized organic waste management applications.

3. Materials and Methods

The experimental investigation was conducted at the University of Technology and Applied Sciences (UTAS), Al Mussanah, Oman, to evaluate methane production from biodegradable kitchen waste, primarily fruit and vegetable residues, under local climatic conditions. In this study, a pilot-scale floating-drum anaerobic digester fabricated from fiber-reinforced plastic (FRP) was employed. The digester had a nominal capacity of 1 m^3 and was designed to process approximately 3 kg of organic waste per day.

The system consisted of a feed inlet, an anaerobic digestion chamber, a floating-drum gas collector, and a digestate outlet. The floating drum was used to collect the biogas generated during anaerobic digestion, while the gas outlet and connected pipeline provided access for gas measurements and combustion testing. The experimental investigation was conducted from January to October 2024 and divided into two operating cycles: Cycle 1 (January–May) and Cycle 2 (July–October). The digester was installed outdoors and operated under naturally varying ambient conditions without externally controlled temperature regulation.



Fig. 2. Pilot-scale digester configuration showing the inlet chamber, digester, gas collector and outlet chamber



Fig. 3. Pilot-scale anaerobic digestion system and gas-use configuration

June was designated as a preparation period for the subsequent operating cycle; therefore, no monthly performance data for June were included in the quantitative comparison. Fruit and vegetable waste collected from local shops and retail outlets in the Al Mussanah region was used as the primary substrate. Visible non-biodegradable materials, such as plastics and metal fragments, were removed, and the organic waste was mechanically reduced in size before being mixed with water. The prepared substrate was diluted at a reported waste-to-water ratio of 1:1.

Cow dung was used during start-up as an inoculum to introduce anaerobic microorganisms into the digestion system. The initial slurry was prepared using a reported mixture of 70% cow dung and 30% water. Following the initial gas-generation and combustion-testing stage, the prepared fruit and vegetable waste was introduced into the digester. The nominal design capacity was approximately 3 kg of organic waste per day. However, actual daily feeding quantities should be reported separately if they differed during operation. Feedstock characteristics, including total solids, volatile solids, and carbon-to-nitrogen ratio, were not available in the experimental dataset; therefore, these parameters were not used to calculate the specific methane yield.

During start-up, the digester was initially charged with the cow-dung slurry prepared at the reported 70:30 cow-dung-to-water ratio. After installation of the floating drum and closure of the gas outlet, the system was operated under outdoor conditions. Accumulated gas was released on Days 3, 6, and 9 following start-up. On Day 12, the collected gas was subjected to a burner-ignition test to assess its combustibility. Following successful ignition, regular feeding with the prepared fruit and vegetable waste slurry commenced.

Throughout the monitoring period, the digester was exposed to seasonal variations in ambient temperature. Consequently, the field measurements represent system performance under naturally varying climatic conditions rather than under a controlled-temperature experimental design. Ambient temperature, digester temperature, and pH were monitored to characterize the operating conditions during the experimental period. Temperature measurements were used to assess seasonal variations in the reactor's thermal environment, while pH measurements were employed to monitor the acid–base conditions within the anaerobic digestion system.



Fig. 4. Experimental equipment, feedstock preparation and monitoring procedures: fruit and vegetable waste preparation; cow-dung and water mixing during start-up;and temperature and pH measurements

Table 1
Principal equipment and specifications reported for the pilot-scale biogas system

Equipment	Description
Anaerobic biogas digester	Nominal volume: 1 m^3; fibre-reinforced plastic; designed for approximately 3 kg of organic waste per day; stated operating-temperature range: 16–45 °C.
Floating drum	Gas collection; the original equipment table states an equivalent LPG-gas capacity of 0.5 kg.
Flow meter	Used to measure gas movement through the pipeline over a period of time.
Piping and plumbing accessories	Gas conveyance and testing connections.
Flexible gas-connection pipe	Conveys generated gas to the burner for combustion testing.
Portable gas analyser	Geotech GA5000 Portable Gas Analyser

The recorded ambient temperature increased from approximately 22 °C in January to 37 °C in July. The digester temperature ranged from approximately 25 °C to 38 °C, with mean values of 29.43 °C during January–May and 35.50 °C during July–October. The recorded pH values ranged from 7.05 to 7.24, with an overall mean of approximately 7.15. However, alkalinity and volatile fatty acid (VFA) concentrations were not available and were therefore excluded from the process stability assessment.

Biogas volume was monitored using a flow meter, while gas composition was analyzed using a Geotech GA5000 portable gas analyser. The gas quality parameters measured included methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S). Daily methane production was calculated by multiplying the total biogas volume recorded during the corresponding measurement period by the methane volume fraction measured by the gas analyser. The resulting methane production was expressed in L CH_4/day. This calculation assumes that the measured biogas volume and methane fraction correspond to the same measurement period and that the analyser readings accurately represent the composition of the biogas produced during that period. Carbon dioxide concentration was expressed as a percentage, whereas hydrogen sulphide concentration was reported in parts per million by volume (ppmv). An initial burner-ignition test was performed to assess the combustibility of the generated biogas. No corrections to standard temperature and pressure conditions were applied in the present analysis.

The experimental data were analyzed to compare digester temperature, pH, methane production, and biogas composition between the two monitoring periods: January–May and July–October 2024. June was designated as a preparation period for the subsequent operating cycle and was therefore excluded from the monthly performance comparison. The percentage change between the mean values of the two periods was determined by subtracting the January–May mean from the July–October mean, dividing the difference by the January–May mean, and multiplying the result by 100.

The performance assessment primarily relied on calculated daily methane production as the principal quantitative indicator of digester performance. Future monitoring should include measurements of feedstock volatile solids loading, verified working volume, and actual slurry throughput to enable the determination of specific methane yield, organic loading rate (OLR), and hydraulic retention time (HRT). These additional parameters would support a more comprehensive and normalized evaluation of anaerobic digester performance. The comparisons presented in this study quantify the observed differences in field measurements between the two monitoring periods. Accordingly, the reported percentage changes should be interpreted as descriptive indicators of

seasonal performance variation rather than evidence of a causal relationship or statistically established treatment effect under controlled experimental conditions.

4. Results and Discussion

The variations in ambient and digester temperatures during the monitoring period are presented in Figure 5. The ambient temperature increased from approximately 22 °C in January to 37 °C in July, while the digester temperature ranged from approximately 25 °C to 40 °C. The mean digester temperature increased from 29.43 °C during January–May to 35.50 °C during July–October. As the reactor operated without external temperature control, its thermal conditions were influenced by variations in the surrounding environment. However, the effects of temperature on digester performance cannot be independently isolated from other operational factors under the field-based experimental conditions.

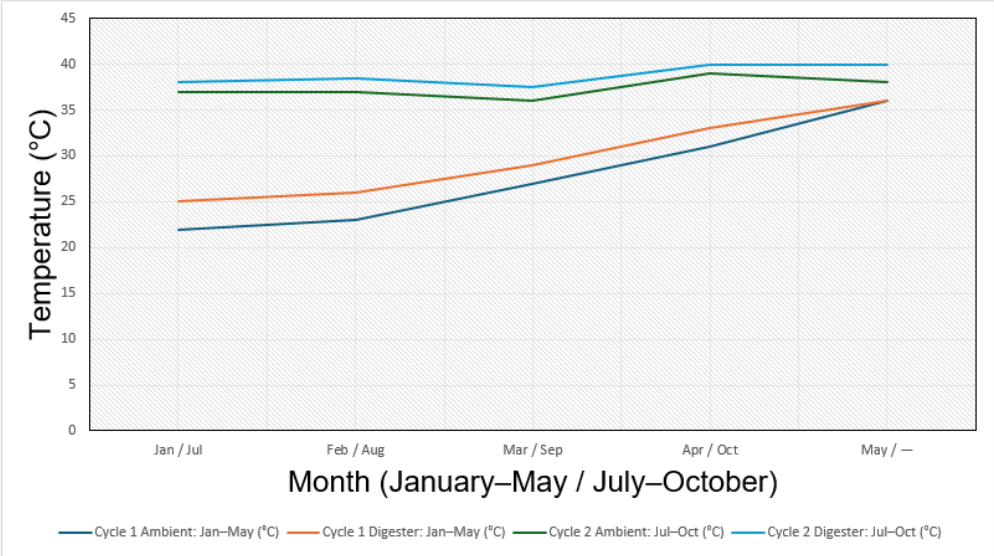


Fig. 5. Monthly variation in ambient and digester temperature during the reported monitoring period

The monthly variation in pH during the monitoring period is presented in Figure 6. The recorded pH values ranged from 7.05 to 7.24, with an overall mean of approximately 7.15. This relatively narrow range indicates that the digestion system maintained near-neutral pH conditions throughout the monitoring period. Such conditions are generally favourable for methanogenic activity. However, pH measurements alone are insufficient to confirm long-term process stability, as the response of the digestion system to volatile fatty acid (VFA) accumulation is influenced by its buffering capacity. Therefore, additional measurements of alkalinity and VFA concentrations would be necessary to provide a more comprehensive assessment of anaerobic digestion stability.

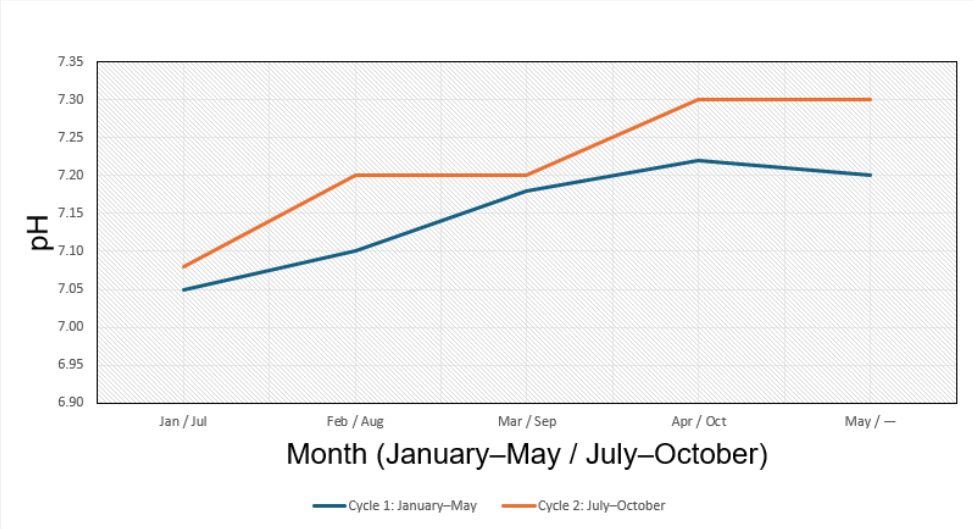


Fig. 6. Monthly variation in pH during the reported monitoring period

The monthly variation in calculated methane production during the monitoring period is presented in Figure 7. Methane production increased from 66.00 L/day in January to 135.45 L/day in May. During the warmer observation period, methane production was 123.00 L/day in July, increased to 144.00 L/day in September, and reached a maximum of 146.00 L/day in October. The mean daily methane production increased from 99.82 L/day during January–May to approximately 137.00 L/day during July–October. This represents an increase of approximately 37.14 L/day, corresponding to 37.25%. Over the same periods, the mean digester temperature increased from 29.43 °C to 38.00 °C. These observations indicate higher methane production during the warmer monitoring period. However, the observed increase cannot be attributed solely to temperature, as other operational factors may also have influenced methane generation under the field-based experimental conditions.

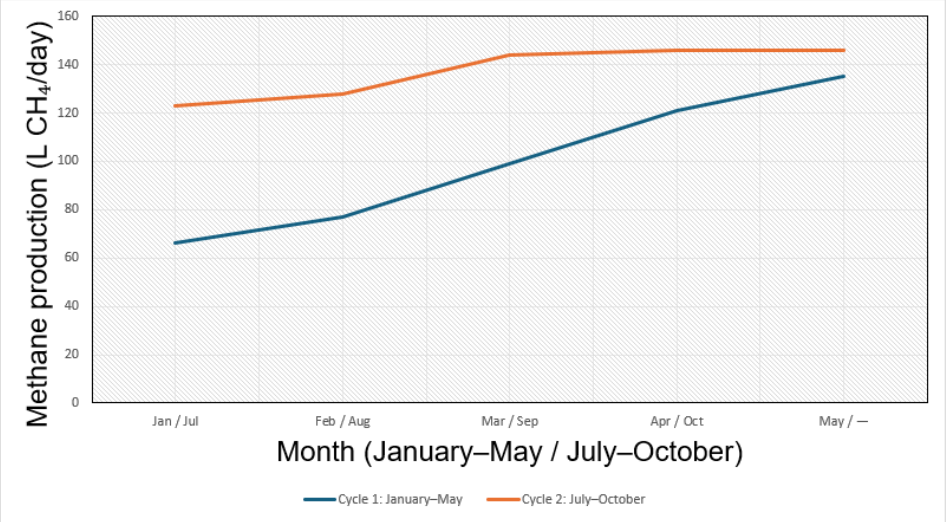


Fig. 7. Monthly variation in calculated methane production

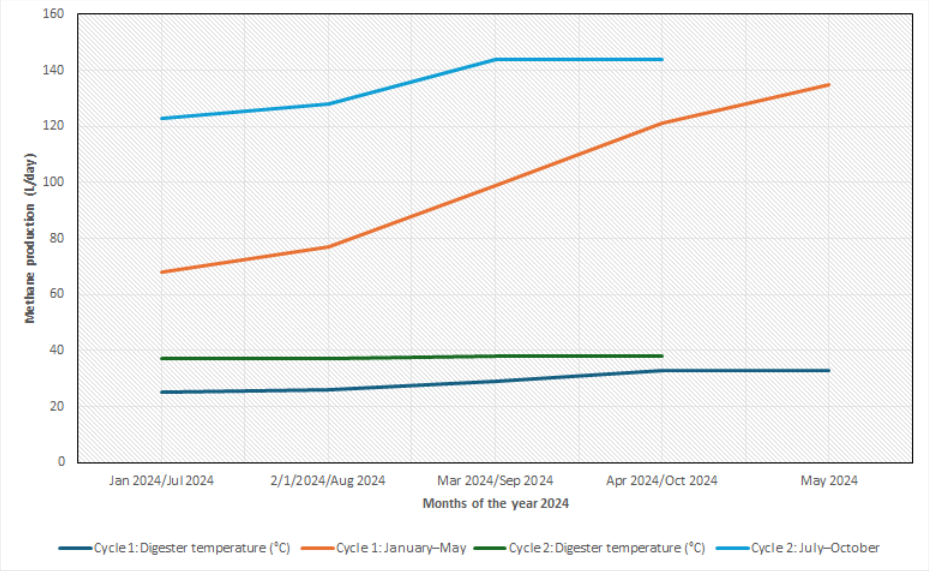


Fig. 8. Relationship between digester temperature and calculated methane production

The relationship between digester temperature and calculated methane production is illustrated in Figure 8. The concurrent increase in mean digester temperature and methane production suggests a possible association between warmer operating conditions and higher methane output. However, the monthly variation in methane production did not exhibit a strictly monotonic relationship with temperature. Methane production reached 144.00 L/day at a reported digester temperature of approximately 35 °C. This observation indicates that methane production may also have been influenced by other factors, including feedstock characteristics, organic loading rate, feeding consistency, and operational conditions. The reported 37.25% increase represents the observed difference in mean calculated daily methane production between the two monitoring periods and should not be interpreted as a direct causal effect of temperature on methane generation.

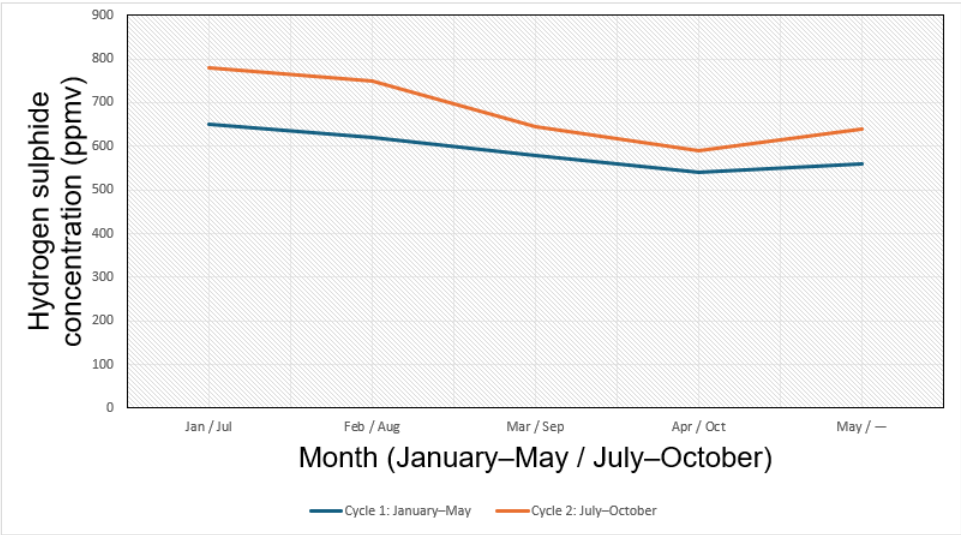


Fig. 9. Monthly variation in hydrogen sulphide concentration during the reported monitoring period

The monthly variation in hydrogen sulphide (H_2S) concentration during the monitoring period is presented in Figure 9. The recorded H_2S concentration was approximately 650 ppmv in January, decreased to 540 ppmv in April, and subsequently increased to 780 ppmv in July before declining to

660 ppmv in October. The mean H_2S concentration increased from 590 ppmv during January–May to 701 ppmv during July–October, representing an increase of approximately 18.8%.

The increase in mean H_2S concentration coincided with higher methane production during the warmer monitoring period, indicating that the increase in methane output was not accompanied by a corresponding reduction in H_2S concentration. Hydrogen sulphide production during anaerobic digestion is influenced by several factors, including feedstock sulphur content, sulphate availability, and microbial activity. These observations are broadly consistent with previous studies on food-waste anaerobic digestion, which have identified substrate characteristics, operating temperature, and feeding strategies as important factors influencing methane production and process stability [4–11].

The increase in calculated methane production during the warmer observation period suggests that temperature may have contributed to the observed variation in digester performance. However, the simultaneous changes in methane production and H_2S concentration do not establish a direct causal relationship, as variations in feedstock composition and other operational conditions may also have influenced the results.

5. Conclusions

This study investigated the potential for biogas production from kitchen waste, particularly fruit and vegetable residues, using a pilot-scale floating-drum anaerobic digester. The 1 m^3 biodigester was operated outdoors under naturally varying climatic conditions, with cow dung serving as the initial microbial inoculum and prepared kitchen waste used as the subsequent feedstock. A comparison of the January–May and July–October 2024 monitoring periods revealed an increase in mean calculated methane production from 99.82 to 137.00 L/day, representing an absolute increase of approximately 37.18 L/day and a relative increase of 37.25%. The recorded pH values ranged from 7.05 to 7.24, with an average of approximately 7.15, indicating near-neutral conditions generally favourable for methanogenic activity. Meanwhile, the mean hydrogen sulphide (H_2S) concentration increased from 590 to 701 ppmv, corresponding to an increase of approximately 18.8%, indicating that higher methane production coincided with increased H_2S concentrations. Although warmer operating conditions were associated with greater methane production, the influence of temperature could not be independently distinguished from other operational factors, including feedstock composition, organic loading, and feeding consistency. Overall, the findings provide preliminary field-based evidence of the potential for converting locally available kitchen waste into biogas under the climatic conditions of Al Mussanah, Oman. However, the absence of volatile solids measurements, verified hydraulic retention time, alkalinity data, and standardized gas-volume measurements limits the assessment of conversion efficiency and the interpretation of underlying process mechanisms. Future investigations should incorporate replicated experimental monitoring, comprehensive feedstock characterization, standardized gas measurements, and techno-economic assessments to establish the reproducibility of the findings, quantify specific methane yield, and evaluate the technical and economic feasibility of wider implementation of decentralized anaerobic digestion systems.

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