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Enhancing biochar-assisted co-digestion of food waste and sewage sludge using cow dung as methanogenic bacteria inoculum: Effect of biochar incorporation

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ABSTRACT

The mono-digestion of sludge in biogas production has limitations due to its inefficient process. To overcome this issue, co-digestion with food waste at an optimal mixing ratio can be applied to enhance biogas production. Additionally, further optimization can be achieved by adding biochar, which acts as a stabilizer and increases the systems buffering capacity. This study investigates the role of biochar as a process stabilizer in biogas yield through the co-digestion of food waste and sewage sludge. The substrates consisted of food waste and sewage sludge mixed at a 4:1 ratio, with cow dung serving as the methanogenic bacteria inoculum in a 1:1 ratio. Fermentation was performed in an 11 L reactor at 38 °C, pH 7 ± 0.2, and an agitation speed of 80 rpm, with biochar added in varying amounts of 0 g/L, 0.5 g/L, and 1.5 g/L. Parameters analyzed included pH, m-alkalinity, total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), and biogas volume. Results showed that a biochar addition of 1.5 g/L achieved best performance compared to 0 g/L and 1 g/L, producing 3.19 L/gVS.day of biogas. The optimal composition of methane, carbon dioxide, and hydrogen sulfide was 76.00%, 23.13%, and 0.31% (v/v), respectively, with a final VS reduction of 12,000 mg/L. Biochar addition significantly improved process stability and biogas production, highlighting its potential to enhance efficiency and support sustainable industrial-scale waste management.

Keywords: biochar, biogas, co-digestion, cow dung, food waste, sewage sludge.

INTRODUCTION

Biogas production using mono-substrate materials like food waste or sludge through anaerobic digestion systems has been widely researched and implemented, yet it still encounters various challenges. While food waste mono-digestion is theoretically viable for anaerobic biogas production, practical applications often face several issues. These include process instability, the buildup of volatile fatty acids (VFAs), foaming, pH reduction, imbalanced C/N ratios, insufficient micro and macronutrient availability, and biogas output that fails to reach optimal levels (Polo et al., 2018). The mono-digestion of sludge is considered inefficient due to its low organic content, inadequate carbon sources, the presence of organic materials that are difficult to biodegrade, and the potential occurrence of toxic substances such as antibiotics that hinder methanogenic activity. Furthermore, the low energy potential and limited organic load of sludge in mono-digestion often result in the underperformance of anaerobic digestion systems.

To address these limitations, the anaerobic co-digestion of food waste with sewage sludge at an optimal mixing ratio can be utilized. This approach improves substrate utilization, enhances biomethane production, stabilizes the process by balancing the C/N ratio, addresses nutrient deficiencies, and neutralizes toxic substances present in the co-substrate (Cheng et al., 2016). This method provides significant benefits for integrated energy production, waste management, climate protection, and sustainable development. Additionally, the co-digestion of sludge and biomass facilitates a shift toward a low-carbon economy (Cheong et al., 2022).

Inhibition in anaerobic digestion has been addressed through various approaches, including bacterial cell acclimatization, operating under thermophilic conditions, and reducing inhibitor concentrations through dilution or co-digestion with other substrates. However, these approaches are unable to completely eliminate inhibitors from the process, which can lead to the accumulation of inhibitor from the system and ultimately destabilize the anaerobic digestion process. Consequently, exploring techniques to remove, immobilize, or reduce the bioavailability of inhibitors is essential (Fagbohungbe et al., 2017). Among these strategies, the use of biochar has gained recognition as a promising approach to mitigate challenges caused by toxic inhibitory compounds (Ambaye et al., 2021). As an adsorbent, biochar has garnered increasing interest for its ability to improve recovery rates during substrate-induced inhibition and minimize nutrient losses throughout the anaerobic digestion process (Sunyoto et al., 2016).

Optimization of anaerobic digestion performance enhancement can occur because biochar has alkaline properties, which can improve buffer capacity. It also has adsorption capabilities that can reduce inhibition by acid-ammonia, sulfide, and other inhibitors, ensuring that the methanogenesis process in anaerobic digestion is not hindered. Additionally, biochar improves the decomposition rate of dissolved organic material and VFAs, promotes microbial enrichment, and enhances interspecies electron transfer (Liu et al., 2022). Inhibitory substances are adsorbed onto the biochar surface through mechanisms such as precipitation, electrostatic attraction, and ion exchange, facilitated by functional groups like hydroxyl, carbonyl, carboxylate, and amine groups present in the biochar. This adsorption mitigates negative impacts, improving the performance and stability of the anaerobic digestion process (Osman et al., 2022).

Figure 1 provides a detailed depiction of the key components and process flows within the system developed to increase biogas production volume. This study explores a comprehensive approach to improving production systems for biogas generated from food waste and sewage sludge. The novelty of this research lies in optimizing anaerobic digestion stability using biochar through physical processes. By employing a batch reactor, this systematic modification significantly boosts the efficiency of anaerobic

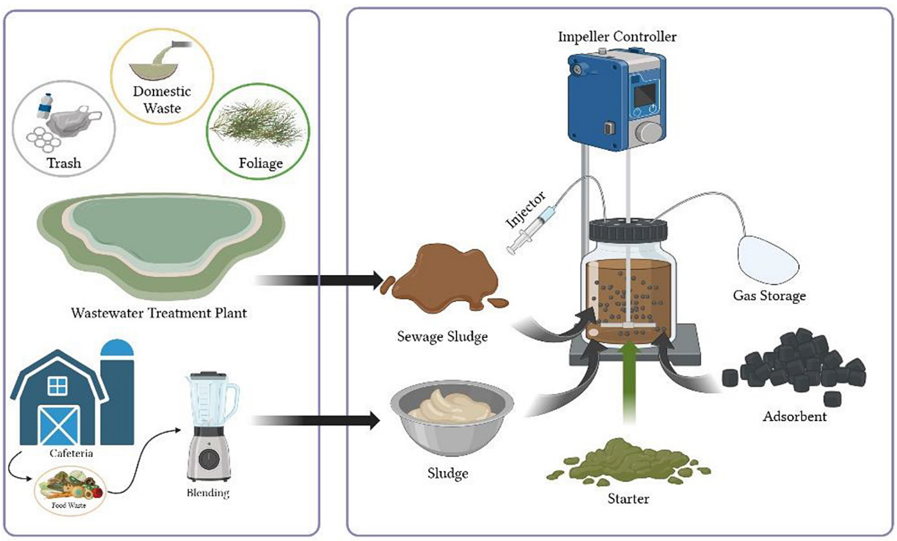

Figure 1. Illustrative diagram of biochar-assisted anaerobic co-digestion

co-digestion, with biochar playing a crucial role in stabilizing the digestion process. The findings demonstrate promising advancements in process recovery rates and provide a pathway to minimize nutrient losses during the digestion process. Additionally, the study holds significant potential for the agricultural industry by offering a sustainable approach to converting waste streams into valuable resources. This integrated method lays a solid foundation for future innovations in anaerobic digestion stabilization technology and its practical implementation in industrial operations

MATERIALS AND METHODS

Material

The main raw materials used in this study include carbohydrate-based waste collected from the X canteen and sewage sludge derived from the Tirtanadi Cemara wastewater treatment plant (WWTP). Prior to use, each raw material was characterized to determine the parameters. The inoculum used was derived from biogas effluent produced by the pilot plant at the Ecology Laboratory, Universitas Sumatera Utara. Meanwhile, the biochar was obtained from a previous study where it was produced from empty palm oil bunch pellets using a microwave pyrolysis process.

In addition, various supporting chemicals were utilized for analysis during the experiments, including hydrochloric acid (HCl) 37%, natrium hydroxide (NaOH), natrium bicarbonate ($NaHCO_3$), potassium dichromate ($K_2Cr_2O_7$), mercury (II) sulfate ($HgSO_4$), silver sulfate (Ag_2SO_4), ammonium iron (II) sulfate hexahydrate $[(NH_4)_2Fe(SO_4)_2 \cdot {}_6H_2O]$, and ferroin indicator ($C_{36}H_{24}FeN_{62}^{+}$) obtained from Merck KGaA® (Darmstadt, Germany).

Experimental set-up

This experiment was conducted in Ecology Laboratory, Universitas Sumatera Utara, Indonesia. The fermentation process was carried out in a 12-liter paddle-stirred batch reactor with a working volume of 11 liters at a temperature of 38 °C. The reactor was equipped with a temperature controller, sample injector, and a measuring cylinder to quantify biogas result as shown in Figure 2. The starter and substrate (food waste and sewage sludge), which had been characterized were added into the reactor at a ratio of 50% starter to 50% substrate (with food waste to sewage sludge ratio of 4:1). The fermenter was operated with the addition of biochar in varying amounts of 0 g, 0.5 and 1.5 g/L of raw material, and the pH was maintained at 7 ± 0.2. Once the desired conditions reached mesophilic temperature (38 °C) the mixture was characterized, and these initial characterization results were recorded as data for t = 0.

In this experiment, daily analyses were conducted for pH, M-alkalinity, TS, VS, total TSS,

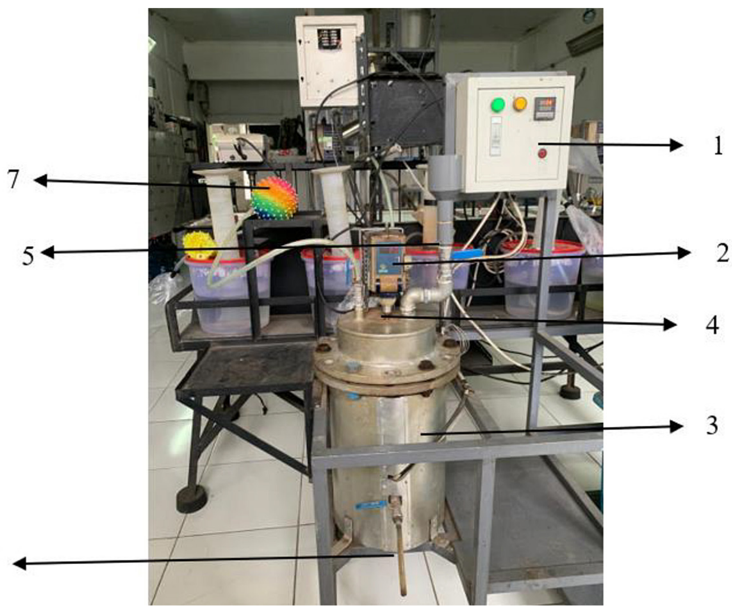

Figure 2. Co-digestion experimental set up: 1 – temperature control panel, 2 – stirrer, 3 – Jar Fermentor, 4 – mixer, 5 – sampling injector, 6 – outlet, 7 – biogas storage

and VSS. Meanwhile analysis of COD and biogas volume were carried out every three days. This analysis was measured using a gas meter connected to the reactor, and the composition of the biogas CH_4, CO_2, and H_2S was analyzed using a gas detector. The experiment was concluded when no further decrease in VS values or biogas production was observed.

RESULT AND DISCUSSIONS

Raw material characteristics

In this study, the raw materials used were a combination of food waste and sewage sludge for co-digestion. Additionally, cow dung was employed as an inoculum to provide microbial populations capable of degrading the substrate into biogas. The inoculum was sourced from a methanogenic anaerobic digester at the Biogas Pilot Plant, USU. Before added into the reactor, both raw materials and inoculum were characterized. The characteristics of the raw materials and inoculum utilized in this study are summarized in Table 1.

Effect of biochar mass on ph and alkalinity profile

The pH level plays a vital role in biogas production throughout the process of anaerobic digestion. This study reveals a strong correlation between pH and alkalinity. Figures 3 and 4 illustrate the pH and m-alkalinity profiles influenced by the addition of biochar mass during biogas production. Figures 3 and 4 show that the pH and alkalinity levels decreased on the first day but slowly increased every day with higher biochar mass during biogas production. Adding biochar improves buffering capacity, stabilizes pH, reduces ammonia acid inhibition, and enriches microbial activity (Liu et al., 2022). pH and alkalinity are critical environmental factors influencing anaerobic digestion stability and microbial growth. Optimal pH ranges between 6.5–7.8 (Quelal and Hurtado, 2023), and alkalinity should be 2500–5000 mg/L (Choong et al., 2018).

Table 1. Characteristics food waste, sewage sludge, and starter

Parameters	Unit	Result			Method
		Food waste	Sewage sludge	Starter (cow dung)	
pH	-	4.58	6.93	7.15	APHA 4500-H
Total solid (TS)	mg/L	156.000	54.000	60.000	APHA 2540B
Volatile solid (VS)	mg/L	152.000	42.000	56.000	APHA 2540E
Total suspended solid (TSS)	mg/L	150.000	46.000	28.000	APHA 2540D
Volatile suspended solid (VSS)	mg/L	145.000	44.000	26.000	APHA 2540E
Chemical oxygen demand (COD)	mg/L	260.000	42.000	48.000	APHA 5220B

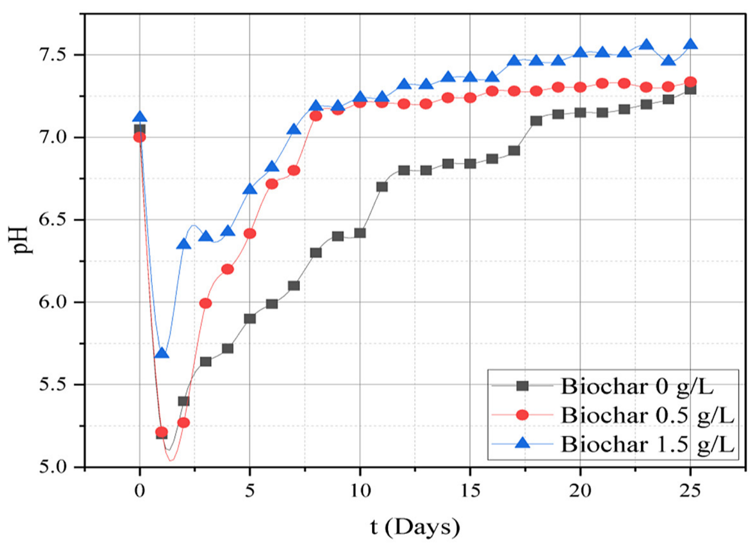

Figure 3. Effect of biochar mass on pH profile

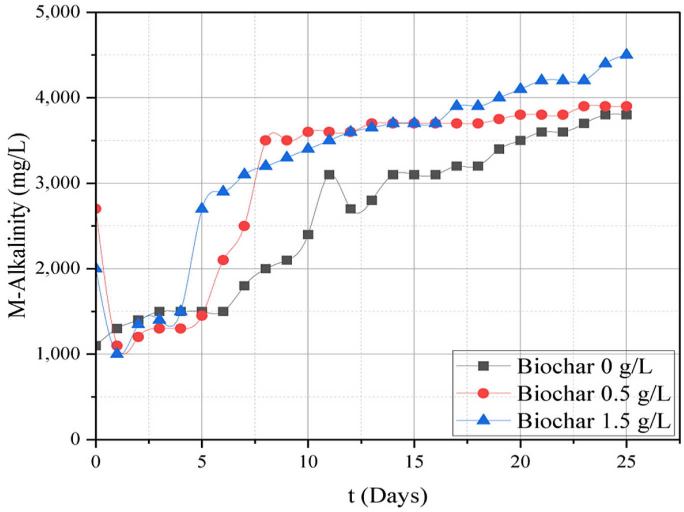

Figure 4. Effect of biochar mass on m-alkalinity profile

Adequate biochar supplementation ensures balance between volatile acid and carbon dioxide production, maintaining stable fermentation conditions.

The observed pH and alkalinity for biochar additions of 0 g/L, 0.5 g/L, and 1.5 g/L ranged from 5.20–7.29, 5.21–7.34, and 5.69–7.56 for pH, and 1.100–3.800 mg/L, 1.100–3.900 mg/L, and 1.000–4.500 mg/L for alkalinity. These values remained within the thresholds required for stable anaerobic digestion, particularly during methanogenesis. The optimal condition was achieved with the incorporation of 1.5 g/L biochar, align with the findings by Jang et al. (2018), who invested methane production with varying biochar concentrations (0, 1, and 10 g/L), the pH data indicated that incorporating biochar into the anaerobic digestion (AD) process significantly improved its buffering capacity compared to systems without biochar.

Effect of biochar mass on volatile solids profile

Volatile solids (VS) concentration serves as an indicator to assess the efficiency of a digestion system. The effect of biochar mass on VS profile is illustrated in Figure 5. Figure 5 shows that the VS profile against the addition of biochar mass fluctuates but generally decreases until it stabilizes as the biochar mass increases in the reactor. This reduction in VS signifies enhanced biogas or methane production, indicating the decomposition of organic compounds within

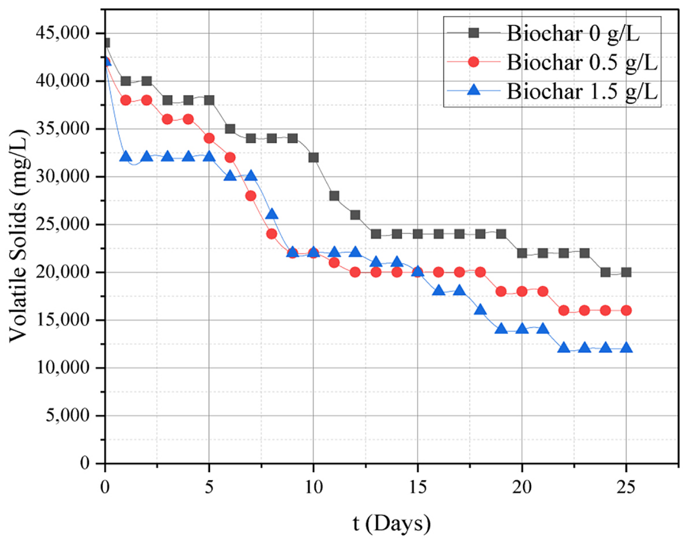

Figure 5. Effect of biochar mass on VS profile

the biodigester (Sarwono et al., 2018). A greater reduction in VS signifies a higher conversion of organic material by microorganisms. The final VS values achieved with biochar additions of 0 g/L, 0.5 g/L, and 1.5 g/L were 20.000 mg/L, 16.000 mg/L, and 12.000 mg/L, with the optimal reduction observed at 1.5 g/L.

Biochar exhibits strong adsorption capabilities because of its large specific surface area (SSA) and high porosity, functioning as a supportive medium for microbial activity. Increasing the biochar mass enhances the efficiency of VS degradation into biogas (Antonangelo et al., 2021). The greater reduction in VS observed at 1.5 g/L of biochar, compared to 0.5 g/L and 0 g/L in this study is parallel with the research performed by Zhuang et al. (2018), who reported that adding 5 g/L of biochar enhances COD removal, improves CH_4 yield, and reduces volatile fatty acids (VFA) by 37.5% compared to the control. At this concentration, biochar not only adsorbs inhibitory compounds but also acts as a growth medium for microorganisms, thereby enhancing VS decomposition and promoting the efficient degradation of organic matter.

Effect of biochar mass on volatile suspended solids profile

Microbial concentration is a key factor in biogas production, as shown by the experiment carried out by Trisakti et al. (2021), the microbial growth profile in the reactor can be indicated by changes in the concentration of volatile suspended solids (VSS) (Trisakti et al., 2021). Figure 6 illustrates the impact of biochar mass on VSS profile.

Figure 6 shows that the VSS profile fluctuated but tended to decrease and eventually stabilize as the biochar mass increased in the reactor. These initial fluctuations in VSS indicate that microorganisms were in an adaptation phase to the new environment. Subsequently, the VSS value decreased during the acclimatization phase due to microbial death, which occurred as a result of the batch process, where microorganisms experienced nutrient deficiencies within the reactor.

The final VSS values obtained with biochar addition of 0 g/L, 0.5 g/L, and 1.5 g/L were 7000 mg/L, 11,000 mg/L, and 19,000 mg/L. This increase in VSS indicates that the distribution of substrates and microorganisms occurred effectively. The addition of biochar promoted microbial adaptation by creating a microenvironment that supported the development of methane-producing bacteria, thereby increasing biogas yield (Rasapoor et al., 2020). Yin et al., (2019) observed that biochar contributes to process stability by promoting the growth of *Enterococcus* bacteria and *Sporanaerobacter*. These bacteria help in breaking down fermentable substrates and facilitate electron transfer to Methanosarcina during methanogenesis. Additionally, biochar enhances the regulation of biofilms and supports the proliferation of beneficial organisms, which

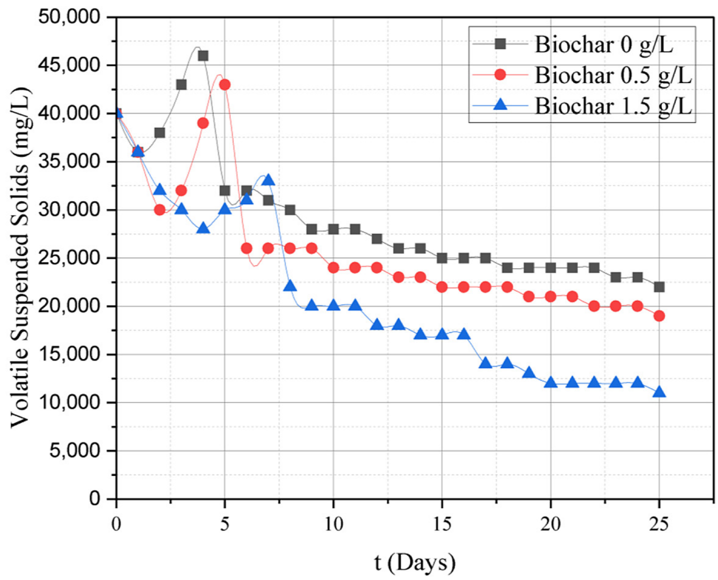

Figure 6. Effect of biochar mass on volatile suspended solids (VSS) profile

improves the performance of the anaerobic digestion process.

Effect of biochar mass on reduction of chemical oxygen demand

Chemical oxygen demand (COD) is an indirect indicator of the quantity of organic compounds in a material, including both biodegradable and non-biodegradable substances (Abdullahi et al., 2021). A significant reduction in COD indicates the successful conversion of substrates into methane (Hamzah et al., 2019). The effect of biochar mass on the reduction of COD can be observed in Figure 7. Figure 7 shows a decrease in COD values with increasing biochar mass in biogas production. The final COD values recorded at biochar additions of 0 g/L, 0.5 g/L, and 1.5 g/L were 38.000 mg/L, 24,000 mg/L, and 16,000 mg/L. The reduction in COD reflects substrate degradation by microorganisms facilitated by biochar as a mediator. Biochars highly porous structure and strong adsorption capacity provide a large surface area for microbial colonization, enhancing interactions between microorganisms and substrates and accelerating biodegradation efficiency (Gryta et al., 2024). The greater COD reduction observed at 1.5 g/L biochar, relative to 0.5 g/L and 0 g/L, in this study aligns with the findings of Zhuang et al., (2018), who demonstrated that adding 5 g/L of biochar enhances COD removal, improves CH_4 yield, and reduces volatile fatty acids (VFA) by 37.5% relative to the control.

Effect of biochar mass on biogas production

The final step in biogas production is methanogenesis. The effect of biochar mass on biogas volume and the cumulative biogas volume results are displayed in Figure 8 and Figure 9.

Figure 8 shows that the addition of biochar at masses of 0 g/L, 0.5 g/L, and 1.5 g/L resulted in fluctuating biogas volumes over time. In this study, biogas production was monitored over 25 days to evaluate the effectiveness of different biochar mass additions. During the initial phase of the process, the biogas volume produced was very low and could be considered negligible; this was due to microorganisms being in the adaptation (lag) phase and not yet achieving optimal biogas production. Over time, the microorganisms entered the exponential phase, where their growth and activity increased, leading to a rise in biogas production volumes.

Figure 9 presents the cumulative biogas volumes for each biochar addition variation. In biogas production without biochar addition (control), a total volume of 0.69 L/g VS day was obtained. The addition of biochar at masses of 0.5 g/L and 1.5 g/L increased biogas production to between 1.77 L/gVS.day and 3.19 L/gVS.day L at the end of the digestion process. This indicates that digesters with biochar addition produced greater volumes of biogas compared to the control digester. Comparable observations were described by Wei et al., (2020), their study utilized batch digester to assess the effectiveness of corn stover

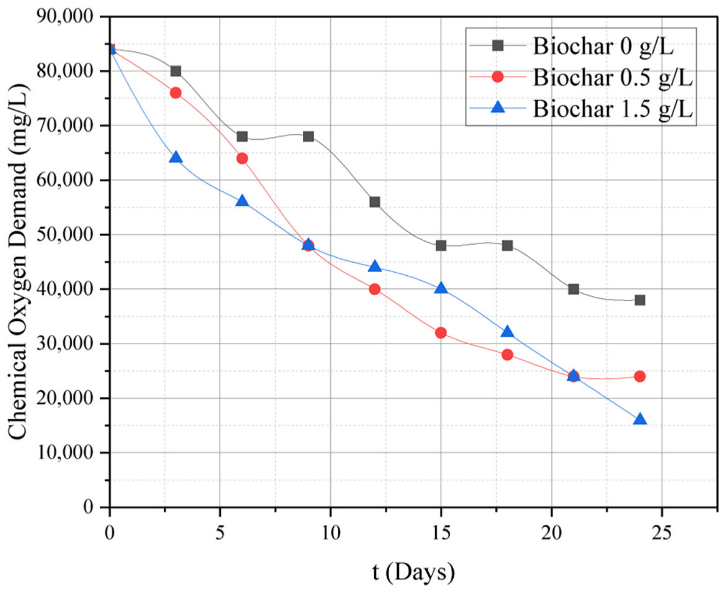

Figure 7. Effect of biochar mass on chemical oxygen demand (COD)

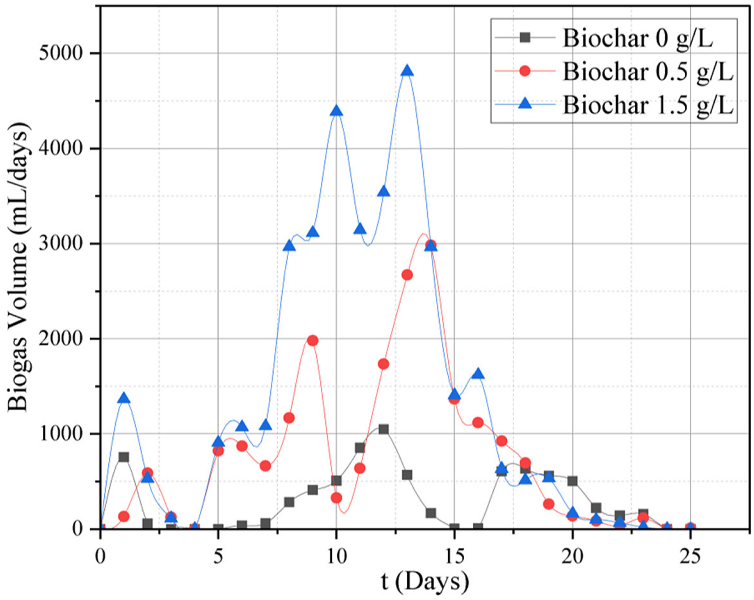

Figure 8. Effect of biochar mass on biogas volume

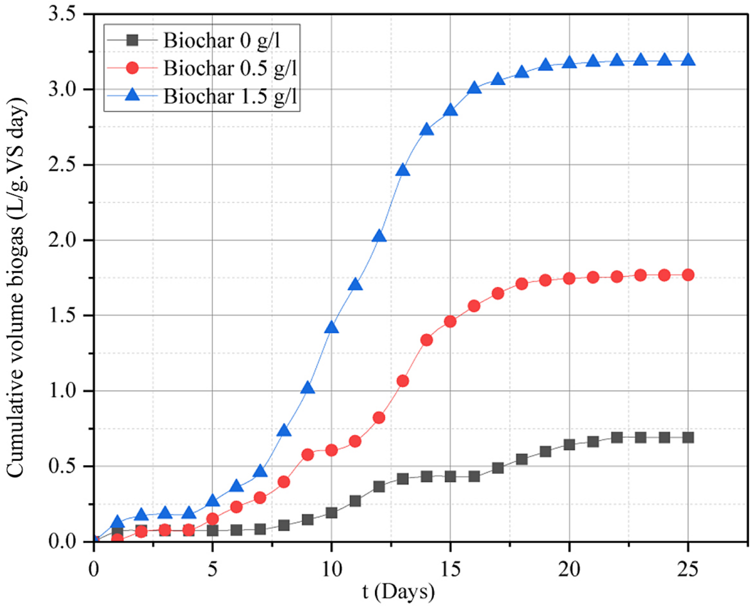

Figure 9. Cumulative volume results of biogas production at various biochar mass

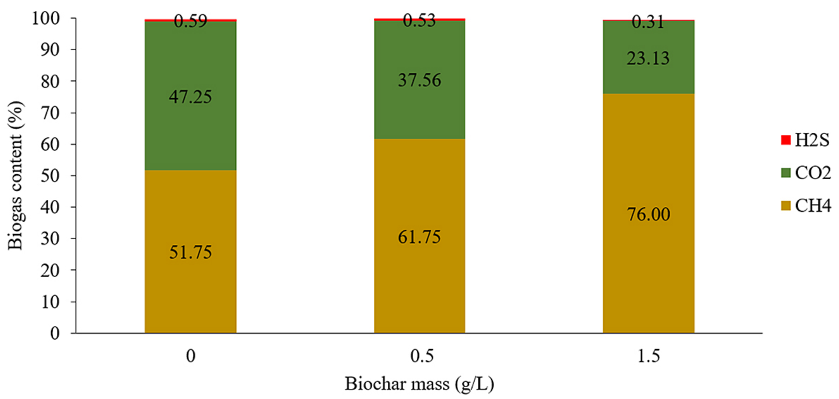

Figure 10. Composition of biogas at various biochar mass

biochar in enhancing the anaerobic digestion of primary sludge (PS). By incorporating biochar mass of 1.82; 2.55; and 3.06 g/g total solids (TS) into the digester, CH_4 yield increased by 8.6–17.8%. Model analysis showed that biochar facilitated the hydrolysis of PS and increased the CH_4 yield. The enhancement in daily and cumulative methane production due to biochar addition can be attributed to the presence of alkaline functional groups on the biochar surface, which can neutralize organic acids produced during the hydrolytic acidification stage of anaerobic digestion, thereby reducing acid inhibition phenomena in the system (Zhang et al., 2019).

Effect of biochar mass on biogas composition

This study measures biogas composition, which is comprised of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) content. The effect of biochar mass on the composition of the produced biogas is shown in Figure 10. Figure 10 depicts that the composition of biogas production increas with the addition of biochar at masses of 0 g/L, 0.5 g/L, and 1.5 g/L. At biochar mass 0 g/L the biogas composition consisted of 51.5% CH_4, 47.5% CO_2, and 0.6% H_2S by volume. Increasing the biochar mass to 0.5 g/L resulted in a composition of 60.00% CH_4, 39.3% CO_2, and 0.5% H_2S by volume. Further, increasing the biochar mass to 1.5 g/L led to a biogas composition of 76.00% CH_4, 23.13% CO_2, and 0.31% H_2S, respectively. This indicates that digesters with more biochar addition produced greater volumes of biogas compared to the control digester.

CONCLUSIONS

In the present work, the incorporation of biochar to the anaerobic digestion process was proven effective in increasing biogas volume and reducing VS and COD levels. The optimal biochar mass of 1.5 g/L showed better results compared to 0 g/L and 1 g/L. At this optimal biochar mass, biogas production reached 3.19 L/gVS.day, with the best biogas content consisting of CH_4 (76.00%), CO_2 (23.13%), and H_2S (0.31%) (v/v). Additionally, process parameters such as pH remained within the optimal range of 6.68–7.56, alkalinity ranged from 2,700 to 4,500 mg/L, final VS decomposition was 12,000 mg/L, and final COD was 16,000 mg/L. Based on these results, this study successfully demonstrates the synergistic of biogas feedstock with biochar as a stabilizer in the methanogenesis process, outperforming the scenario without biochar with a methane yield increase of 46.86% at various biochar mass levels. The potential for enhanced methane production can further be focused on the modification of biochar. This not only exhibits the suggested system but also establishes the foundation for implementation in future industries.

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