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Biogas Production from the Co- and Tri-digestion of Pineapple Wastes with Food Wastes and Pig Manure

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Abstract. Anaerobic digestion (AD) of pineapple wastes (PW) was determined to observe its effects on biogas production when co- and tri-digested with pig manure (PM) and food waste (FW). The highest cumulative biogas yield was seen in R3 (245 mL/g VS), followed by R4 (179 mL/g VS) and R1 (168 mL/g VS), while the lowest was recorded in R2 (150 mL/g VS). Co-digestion of PW with FW showed an increase of 45.8%, while tri-digestion of PW with PM and FW had an increase of 6.55% compared to the biogas yield of mono-digestion. However, co-digestion of PW with PM decreased by 10.7%, indicating an inhibitory effect.

1 Introduction

Among the explored energy sources is biogas generation through anaerobic digestion (AD) as it has the potential to be used as a fuel with high energy content for various applications, but the amount of biogas produced depends on the type of feedstock used. Possible feedstock categories are agricultural residues, animal manure, and food waste (FW). Agricultural residues such as pineapple wastes (PW) can be used to produce biogas, but its low nitrogen content limits the amount of biogas that can be generated. Lignocellulosic wastes, such as PW, are not easily biodegradable when used alone, but the addition of livestock waste can supplement biological activity and increase biogas production [1]. Livestock wastes, such as pig manure (PM), have excellent energy potential and are rich in nitrogen and phosphorus, but their low carbon to nitrogen ratio could result to low biogas yields [2]. However, this problem can be alleviated by adding substrates such as FW to facilitate anaerobic co-digestion, which increases biogas yields by improving system stability and shortening the lag phase. FW form one of the great potentials to tap and harness decentralized energy via anaerobic digesters since about 0.23–0.95 kg of waste is generated per capita all over the world [3].

Numerous studies have yielded encouraging outcomes with respect to anaerobic co-digestion of various waste combinations that are relevant for this study. A study has evaluated that the tri-digestion of FW, kitchen waste, and fruit/vegetable waste produced higher biogas yields

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when compared to co-digestion and mono-digestion systems in the same study. The increased biogas yields of tri-digestion is supported by stronger synergistic effect and stability [4]. Moreover, another study has showcased that the tri-digestion of agricultural wastes (cow manure + corn straw + vines & cow manure + corn straw + wine residue) was lower than the co-digestion of cow manure paired with corn straw or grape leaves [5]. This suggests that proper substrate selection that would synergize well with other substrates for tri-digestion should be considered. Furthermore, there is no available data concerning the tri-digestion of PW, FW, and PM. Hence, the primary aim of this study is to investigate the synergistic effects on the anaerobic digestion of the aforementioned substrates. Specifically, the objective of the study is to determine the biogas yield of mono, co, and tri digestion of PW, PM, FW. Thus, this study can further contribute to the control of waste generation by highlighting the conversion of PW, FW, and PM into biogas that can simultaneously match the supply with the growing demand for energy. Additionally, the current study can support the development of sustainable waste management systems, promotion of bioeconomy and circular economy, and mitigation of greenhouse gas emissions and climate change.

2 Materials and Methods

2.1 Feedstock and inoculum

PW and FW were crushed and homogenized to form a slurry mixture. The two substrates and the PM were refrigerated at 4°C before it was used [6]. On the other hand, cow dung was degassed through incubation for 5 days at 37 C before usage. The substrate-to-inoculum ratio (S/I) used in all runs was 1:1 (VS basis).

2.2 Reactor setup

The AD experiments were conducted in HDPE reactors with a working volume of 600mL while 1000-mL Erlenmeyer flask was used as a vessel for water and NaOH solution (see Fig. 1) [7]. All reactors were purged with N2 for 2 minutes before AD [8]. The experiments were conducted for 45 days at a room temperature of 22-27°C and the reactors were shaken every 24 hours for 2 minutes to increase the digestion efficiency [7]. Table 1 summarizes the batch setup for the reactors.

Table 1. Batch anaerobic experiment controls

Run	PW	FW	PM	Inoculum
R1	✓	-	-	✓
R2	✓	-	✓	✓

R3	✓	✓	-	✓
R4	✓	✓	✓	✓

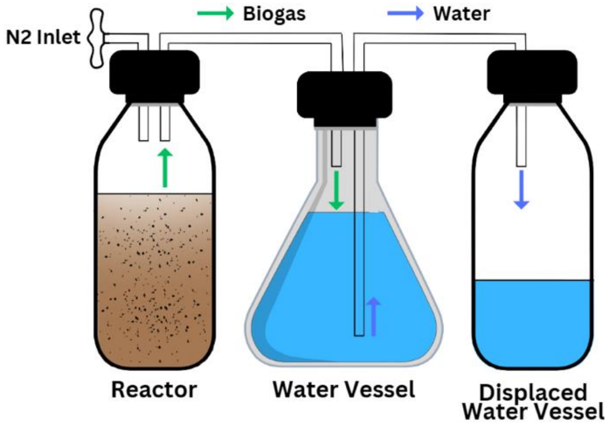

Fig. 1. Reactor setup.

2.3 Analytical methods

Physicochemical characterization of PW, FW, and PM were performed according to standard procedures.

3 Results and discussion

3.1 Characterization of feedstocks

The BOD/COD ratio, TS, VS, and pH values are among the attributes of the feedstocks used in the AD system that are displayed in Table 2. Wastewater biodegradability has been measured using BOD/COD ratios, where a greater value denotes a higher biodegradability. BOD/COD levels over 0.5, 0.3 to 0.5, and below 0.3, respectively, indicate high biodegradability, biodegradability, and unmanageability [6]. It could be referred to Table 2 that all three feedstocks have BOD/COD ratios above 0.5, indicating significant biodegradability. Moreover, the values of VS obtained from PW, FW, and PM were found to be within the specified range [8]. The amount of biogas produced from AD is mostly dependent on the substrate's composition. The VS/TS ratio indicates the substrate's capacity to produce biogas in anaerobic conditions. The ratio enhances the substrate's ability to produce biogas [9]. Additionally, the inoculum and pig manure were slightly basic with a pH of 7.89 and 7.46 while PW and FW were acidic with a pH of 4.54 and 4.73. A pH value of around 6.5-7.5 is recommended for ideal AD conditions [10]. Thus, each run was adjusted for pH with a Ca(OH)2 buffer with a pH of 12.5 before proceeding with AD.

Table 2. Characterization of feedstocks.

Parameter	PW	FW	PM

TS (g/g_{sample})	0.138	0.336	0.326
VS (g/g_{sample})	0.116	0.247	0.216
VS/TS	0.841	0.733	0.661
pH	4.54	7.46	4.73
BOD (mg/kg_{sample})	433507	1405265	328986
COD (mg/kg_{sample})	545148	1481041	477128
BOD/COD	0.80	0.95	0.69

3.2 Biogas production

The daily biogas yields of all the batches throughout the digestion period is presented in Fig. 2. A recurring theme could be observed from the daily biogas yield of the reactors: the initiation of the biogas production (characterized by the miniscule amounts of H_2O production), followed by sharp surge in the amount of yield, then a progressive decline from the peak of the biogas production. These stages are similar to the stages of a typical bacterial growth curve [11].

The first noticeable rise of biogas production occurred on different period for the reactors. Before this period, hydrolysis actively occurs where hydrolytic bacteria Streptococcus and Enterobacter breakdown complex compound to be readily available for the next processes of AD. This is followed by acidogenesis where acidogenic bacteria such as Bacillus, Salmonella, or Lactobacillus produce VFA from the broken-down compounds [12]. The production of VFA is active on $pH > 5$ and stops at acidic environments of $pH < 5$ [13]. This is observed as the pH of the substrates are adjusted within the range of 6.5 to 7.5, while the final pH of the reactors ranged from 3.49 to 4.3, signifying that the production of VFA came to a halt. During the first noticeable rise of biogas production, acetogenesis is engaged where the Syntrophomonas and Syntrophobacter bacteria are responsible for converting the produced VFA into acetic acid, and H_2 and CO_2.

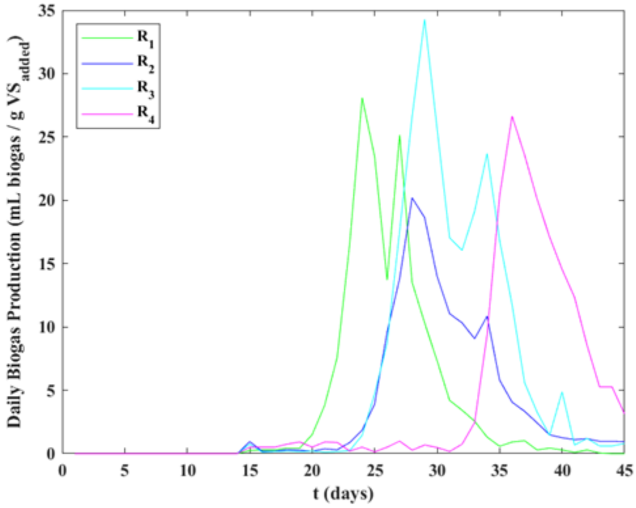

Fig. 2. Daily biogas production profile.

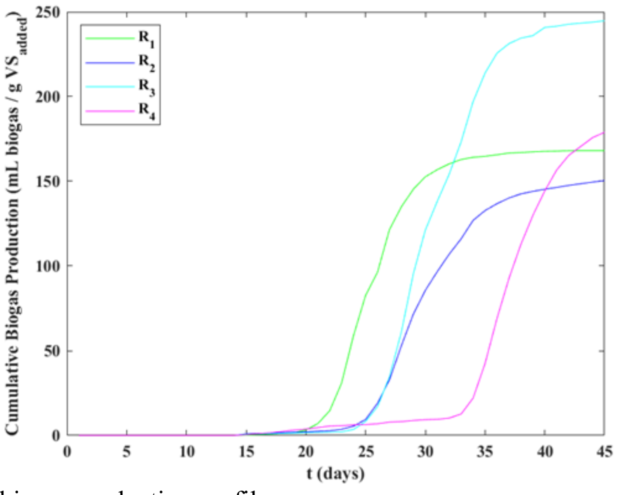

Fig. 3. Cumulative biogas production profile.

The 1st batch (mono-digestion of PW) attained its peak on the 24th day of the digestion, while the co-digestion groups, PW + PM and PW + FW, attained their peak on the 28th and 29th day of the digestion period, respectively. The tri-digestion batches (PW + PM + FW) attained their peak during the 36th and 37th day of the digestion period. This rapid rise of biogas yield is characterized by the occurrence of methanogenesis where Hydrogenotrophic methanogens produces methane from H2 and CO2 while *Acetoclastic* methanogens uses Acetic acid to produce methane [14].

It could be observed in Fig. 3 that the highest cumulative biogas yield was seen in R3 (245 mL/g VS), followed by R4 (179 mL/g VS) and R1 (168 mL/g VS), while the lowest was recorded in R2 (150 mL/g VS). Co-digestion of PW with FW showed an increase of 45.8%, while tri-digestion of PW with PM and FW had an increase of 6.55% compared to the biogas yield of mono-digestion. However, co-digestion of PW with PM decreased by 10.7%, indicating inhibitory effects. It can also be perceived in Table 3 that co-digesting PW with FW and tri-digesting PW with FW and PM gave comparable results with previous literature.

This evidenced that the advanced method, co- and tr-digestion, utilized were effective in enhancing biogas production.

Table 3. Biogas production from related feedstocks.

Feedstock	Yield	Reference
Mono-digestion of PW	287.8 ± 2.1 mL/g VS	[15]
Co-digestion of PW with cow dung	59.09 ± 2.15 mL CH_4/g VS 83.33 ± 6.11 mL/g VS	[16]
Co-digestion of 50% FW and 50% PM with 50% inoculum rate	263 mL/g VS	[17]
Mono-digestion of PW	344.649 mL/g VS	This study
Co-digestion of 50% PW and 50% PM	308.664 mL/g VS	
Co-digestion of 50% PW and 50% FW	427.047 mL/g VS	
Tri-digestion of 33% PW, 33% PM, and 33% FW	406.416 mL/g VS	

3.3 pH and TS-VS reduction

Anaerobic digestion relies heavily on the pH of organic wastes. Between 6.5 and 7.5 is the ideal pH range for anaerobic digestion [12]. The type and composition of the waste determine its initial pH. Anaerobic digestion can cause a drop in pH because it produces volatile fatty acids (VFAs) which are byproducts of the fermentation process [18]. The solution may become more acidic because of the VFA buildup.

The observations in Fig. 4 show that the initial pH values in each reactor are higher than 6.5, which is within the ideal pH range for anaerobic digestion. Nevertheless, all reactors' final pH readings display levels below 6.5, indicating a drop in pH during the anaerobic digesting process. Reactor 1, which only contains PW, notably shows the greatest pH drop. This result is likely related to PW's high carbohydrate content, which causes more volatile fatty acid (VFA) to be produced during the anaerobic digestion processes of hydrolysis and acidogenesis [19]. Although there is still a pH drop in the remaining reactors, it is not as noticeable. This can be linked to the pH-buffering action that PM and FW promote. The alkaline chemicals found in both PM and FW, along with their high protein content, may work to offset the decrease in pH [20].

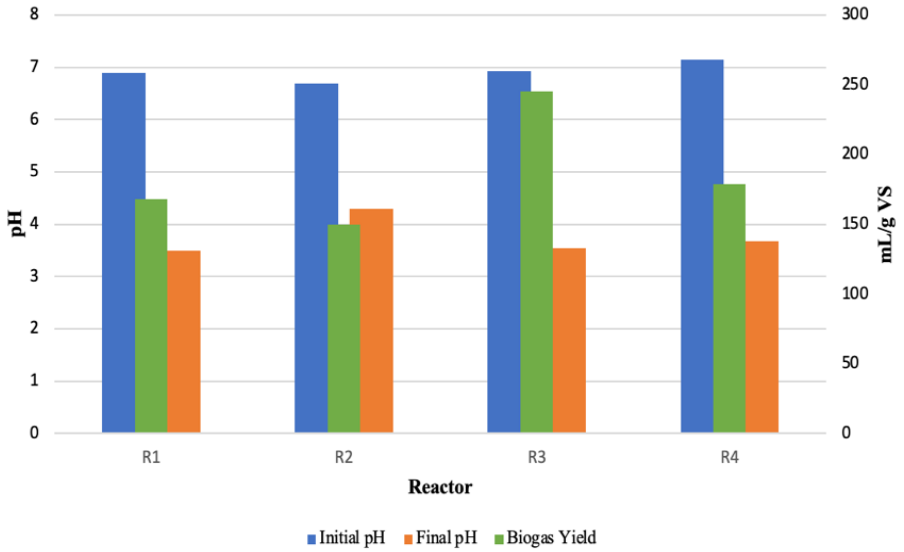

Fig. 4. pH and biogas yield.

Waste that is not volatile is referred to as total solids (TS). Due to the low total solids (TS) content of wet anaerobic digestion (AD), which is usually less than 10%, significant water additions are required, which presents financial difficulties for digestate management. On the other hand, dry AD, which uses substrates with a higher TS content (often ⩾ 15%), shows promise as a substitute. It offers advantages including lower energy requirements, smaller reactor sizes, lower water use, and effective pathogen inactivation [21]. The literature currently in publication shows contradictory links between methane output and TS content. While some research show advantages with increasing TS content, others demonstrate a decrease in methane output. This discrepancy is attributed to differences in the makeup of waste, most especially the biochemical components that include the amounts of fat, protein, and carbohydrates [22].

Fig. 5 presents the initial and final total solids (TS) values for four reactors containing different proportions of food waste (FW), pig manure (PM), and pineapple waste (PW). According to the data, all four reactors' initial TS levels, which range from 0.050 to 0.057, are comparable. The reactors' final TS levels, however, differ greatly from one another. The reactor with the lowest final TS value, Reactor 1 (PW), and Reactor 3 (PW-FW), whereas the reactor with the greatest final TS value, Reactor 4 (PW-PM-FW). Although the extent of the net TS decline differed throughout the reactors, all of them decreased. Reactor 3 experienced the most drop in TS, at 31.6%. Reactor 4 experienced the least amount of TS drop, at 5.26%.

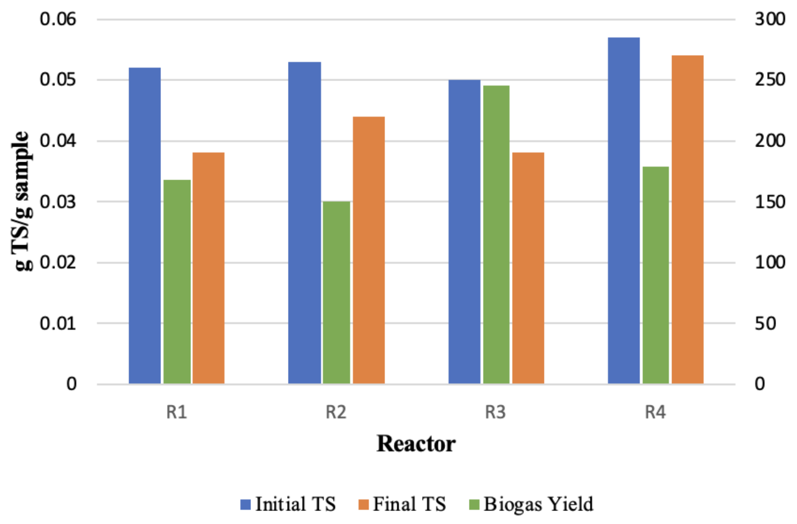

Fig. 5. TS and biogas yield.

On the other hand, all four reactors have significant documented VS reductions, ranging from 20.5% to 63.2%, as seen in Fig. 6. The reactor with the largest VS reduction and biogas generation was R3, which held a mixture of food waste and pineapple waste. The FW's easy biodegradability is probably the cause of this [23]. As seen in Fig. 6, reactors without PM (Reactors 1 and 3) displayed a smaller percentage drop in VS compared to reactors with PM (Reactors 2 and 4), suggesting that PM may have an inhibiting influence on the digestive process.

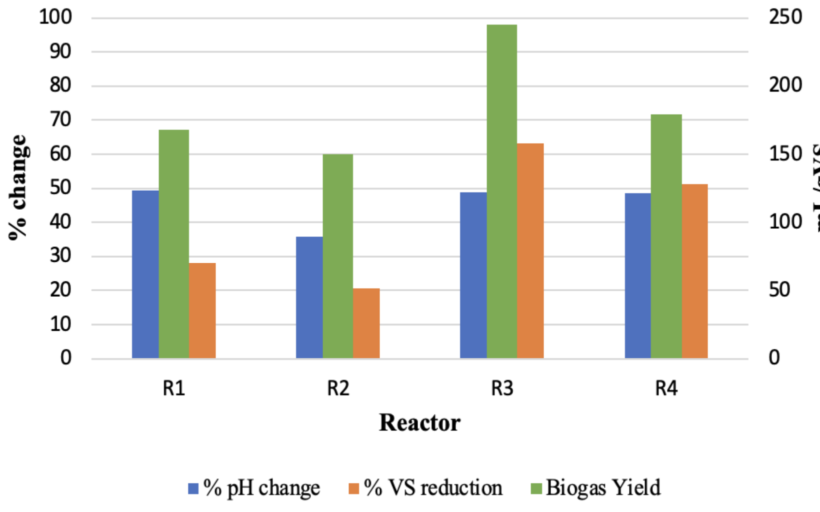

Fig. 6. %pH change, %VS reduction and biogas yield.

4 Conclusion

The tri- and co-digestion of pineapple waste (PW) with pig manure (PM) and food waste (FW) was examined to determine its effects on biogas production. The research found that the co-digestion of PW with FW had the highest cumulative biogas yield at 245 mL/g VS which had a 45.8% increase with that of PW alone at 168 mL/g VS. It was also found that co-digestion with PM resulted in 10.7% decreased yields at 150 mL/g VS while tri-digestion with PW, FW and PM had a 6.55% increase with 179 mL/g VS. Tri-digestion of these wastes was also investigated based on their methane content which produced 130 mL/g VS of methane. This indicated that tri-digestion of PW, PM, and FW has a methane content of 72.6%.

Notable decreases in VS were also noted by the study, with variations in reactors ranging from 20.5% to 63.2%. The reactor comprising FW and PW showed the greatest VS reduction and biogas generation, which can be attributed to FW's easy biodegradability. PM-containing reactors had poor VS decrease and a lesser percentage decline in VS.

Overall, this work highlights the intricate relationship between substrate types and kinetic modeling and offers crucial insights into optimizing AD procedures for biogas production. It highlights the possibilities of using a variety of organic waste streams in AD systems and emphasizes the necessity of carefully controlling operational parameters in order to optimize the yield of biogas.

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