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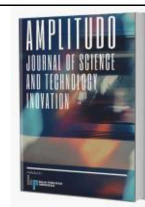

Enhancing Biogas Production Via Single and Mixing Anaerobic Digestion of Food Waste and Coconut Waste

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Abstract: Food waste (FW) and coconut waste (CW) contribute significantly to environmental pollution, highlighting the need for sustainable waste management solutions. This study investigates the anaerobic digestion (AD) of FW and dried CW, comparing the efficiency of single and mixing digestion approaches in biogas production. The research examines the physical properties of both substrates and evaluates their biogas production potential using anaerobic single and mixing digestion techniques. Standard methods were employed to analyse total solids (TS), volatile solids (VS), and pH. The experiments were conducted in Duran bottles at mesophilic temperatures (26°C–32°C) with a se t inoculum-to-sample ratio. Biogas production was measured using the water displacement method over 10 days. The TS values for FW and CW were 46.00% (±0.05) and 60.00% (±0.04), respectively, while their VS values were 97.73% (±0.05) and 93.75% (±0.07), respectively. The pH analysis indicated that both substrates were in an acidic state; the value was near the optimum value of AD. Biogas recovery results indicates that mixing digestion of FW and CW produced the highest yield, reaching 786.00 mL (±0.02) on day 8. In contrast, single digestion of FW and CW yielded 425.0 mL (±0.04) (day 8) and 475.0 mL (±0.05) (day 7), respectively. These findings demonstrate that mixing digestion significantly enhances biogas production due to improved nutrient balance and microbial activity. Additionally, mixing digestion stabilizes the AD process, leading to greater efficiency and energy recovery. This study highlights the potential of FW and CW as viable feedstocks for biogas generation, offering a sustainable waste management alternative. By optimizing AD systems, this research contributes to renewable energy development and supports sustainable waste utilization practices.

Keywords: Anaerobic Digestion; Biogas; Coconut Waste; Food Waste.

Introduction

Food waste (FW) and coconut waste (CW) are major contributors to global environmental issues, with substantial implications for waste management, resource depletion, and climate change. According to global estimates, an individual produces approximately 160–295 kg of food waste per year, with wastage occurring at different stages of the food supply chain, as well as production, transportation, storage, and consumption (Chrispim et al., 2021; Selaman & Wid, 2016). CW, which includes husks, shells, and leaves, is another abundant agricultural byproduct, mainly in tropical regions. The improper disposal of these organic wastes leads to severe environmental challenges, including methane (CH_4) emissions from landfills, soil contamination, and increased carbon footprints (Mecha & Kiplagat, 2023).

Currently, waste management techniques such as landfilling and incineration are widely used; however, both methods present significant drawbacks. Landfilling consumes valuable land space and releases harmful greenhouse gases (GHGs), while incineration is energy-intensive and costly, often producing toxic pollutants (Wid & Selaman, 2025). As a result, there is an urgent need for sustainable waste management strategies that

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not only reduce waste accumulation but also encourage resource recovery (Abd Hammid et al., 2019). One promising approach is AD, a biochemical process in which microorganisms break down organic matter in an oxygen-free environment, producing biogas and nutrient-rich digestate. AD offers multiple benefits, including renewable energy generation, waste volume reduction, and improved environmental sustainability (Andrade et al., 2020). However, the efficiency of the AD process depends on various factors, such as the type of substrate, microbial activity, and process conditions (Bhatt & Tao, 2020).

Single-substrate digestion may suffer from low biogas yields due to nutrient imbalances, while mixing digestion, which involves combining two or more organic wastes, has been shown to enhance biogas production by improving nutrient availability, optimizing carbon-to-nitrogen (C/N) ratios, and increasing microbial diversity (Firmo et al., 2022; Mohammad et al., 2021). This study investigates the AD of FW and CW, comparing the efficiency of single and mixing digestion approaches in terms of biogas production. The objectives of this research include analysing the physical properties of FW and CW by examining total solids (TS), volatile solids (VS), and pH levels to determine their suitability for AD. Additionally, the study evaluates the impact of single and mixing digestion on biogas production by measuring the volume of biogas generated over a set period using the water displacement method. By optimizing AD systems, this research aims to enhance renewable energy production and promote sustainable waste management solutions. The findings align with several United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation, and Infrastructure), Goal 11 (Sustainable Cities and Communities), and Goal 13 (Climate Action). The insights gained from this study will contribute to improving biogas recovery from organic waste, supporting environmental conservation efforts, and reducing dependence on fossil fuels.

Method

Sample Collection and Preparation

Raw FW (bread and biscuits) was collected at Menara Ilmu Cafe, located in the UiTM Sabah Branch, Kota Kinabalu, Sabah.While CW (Dried coconut leaves) was collected from the Unit Ladang area, UiTM Sabah branch (Figure 1). Both samples were cut to a small size of about 3-5 mm before being analysed. The purpose is to facilitate the AD efficiency process. The sludge that was used in this experiment was collected from the Unit Ladang Pond in UiTM Sabah Branch and it were kept in an anaerobic state at temperature $35^{o}C$ (±1) in an incubator for one week before being used. This activated the facultative anaerobic bacteria in the sludge (Ibro et al., 2022).

(a) (b)

Figure 1. (a) FW; and (b) CW

Determination of physical properties of FW and CW

The standard procedure for determining the physical properties of the raw materials was done according to Buckel (2021), the purpose of this study was to identify whether the samples could be used to undergo the AD process.

Determination of Total Solids (TS)

Firstly, an empty crucible was weighted using an analytical balance. Then, the crucible was filled with a FW sample and then weighted. All the weight was recorded. Next, the FW sample with the crucible was placed in an oven and heated at $105^{O}C$. This process was done for 24 hours. Next, the FW sample was placed in a desiccator to prevent the re-absorption of moisture by the sample. To increase the reliability of the measurement, FW samples were tested in triplicate. The TS was calculated using Equation 1. This procedure was repeated for CW.

$$TS\ (\%) = [(A-B)\ /\ (C-B)] \times 100\% \quad (1)$$

TS is referred to as Total Solid (%)
A = crucible weight + dry sample weight (g)
B = crucible weight (g)
C= crucible weight + wet sample weight (g)

Determination of Volatile Solids (VS)

To determine the VS, a FW sample from section (a) was placed in a muffle furnace at $550_{o}C$ for a total of 4 hours. Then, the sample was placed into a desiccator and weighted (APHA, 2010). Once the procedure was completed, the percentage of VS was calculated using Equation 2. This procedure was repeated for CW.

VS (%) = [(A-C)/ (A-B)] x 100% (2)

VS is referred to as Volatile solid (%)
A = crucible weight + dry sample weight (g)
B = crucible weight (g)
C= crucible weight + ash sample weight (g)

Determination of Ph

The ratio of the FW sample to distilled water was set at 1:10 (w/v). The FW sample was placed in a bottle and shaken by using an orbital shaker at a speed 130 rpm for 24 hours. In order to determine the pH, the FW sample was filtered using a vacuum filter, and the liquid part was taken to determine the pH. The pH was measured by using a pH meter (Xu et al., 2022). This procedure was repeated for CW.

Operation start-up for AD process

The experimental work was performed using a Duran bottle with a working volume of 400 mL. Digestion tests were performed in an incubator. The sample to sludge ratio was fixed at 1.0:2.0. While the temperature use at mesophilic conditions in the range of 26°C - 32°C.The Duran bottle was charged with sample FW and CW. With also the mixing substrates of both wastes. The pH was controlled at 6.8 to 7.2 by using 1.0 M HCl and 1.0 M NaOH. The digestion time for each digester was set up for 30 days. During the experiment, the gas was released once a day. The determination of gas recovery was done using the water displacement technique (Selaman & Utomo, 2024). The volume of gas recovery was calculated using Equation 3.

Vol gas recovery (mL) = Vol distilled water (mL) (3)

Data Analyses

Data obtained from the experiments were analyzed in the IBM SPSS Statistic 22.0 statistical software package. For the summary statistics, the results were given as mean ± standard deviation. The appropriateness of the normal distribution of the data was assessed with Shapiro-Wilk normality test. For the comparison of different parameters applications, one way-ANOVA, and for multiple comparison test, Student-Newman-Keuls test were used. $P < 0.05$ was considered as the statistical significant value.

Result and Discussion

Physical Properties of FW and CW

Table 1 shows that the TS values of FW and CW from this study were 46.00% (±0.02) and 64.00% (±0.05), respectively. Both waste TS values differ due to variations in their composition, moisture content, and structural characteristics (Andrade et al., 2020).TS represents the total amount of solid material in a sample, including both organic and inorganic components, after removing water. FW typically contains a higher moisture content due to its composition, which includes perishable items such as bread and noodles. Besides that, this study was focused on the FW which are mainly bread and noodles. These food items naturally retain a significant amount of water, leading to a lower TS value 46.00% (±0.05). In contrast, CW, particularly dried coconut leaves or husks, has a more fibrous and lignocellulosic structure with a lower moisture content, resulting in a higher TS value 64.00% (±0.02). The high fiber content in CW contributes to its solid fraction, making it more resistant to microbial degradation compared to FW (Vidal-Antich et al., 2022). However, Ahuja et al. (2024), stated that TS values of more than 30.00% suggest high TS, which can influence producing a high amount of biogas. Additionally, (Mecha & Kiplagat, 2023) reported that a high TS indicates that the waste is not suitable for landfilling as it can undergo the AD process in an open space and will consequently contribute to the release of GHGs. A high TS value also represents a high volume of waste; thus, it will need more space for landfilling. The present TS value from other study results showed a difference with the studies by (Abd Hammid et al., 2019; Mecha & Kiplagat, 2023; Selaman & Utomo, 2024) (Table 1). The difference in the value could be due to the different types and compositions of samples used in the studies.

Table 1. Physical properties data for current and previous studies

References	Types of Waste	TS (%)	VS (%)	pH
Current study	FW	46.00 ± 0.05	97.73 ± 0.03	5.13 ± 0.02
	CW	64.00 ± 0.02	93.75 ± 0.03	6.37 ±0.04
Abd Hammid et al. (2019)	Banana peels	17.18 ± 0.00	85.56 ± 0.00	5.61± 0.00
Mecha & Kiplagat (2023)	Kitchen Waste	36.20 ±2.34	96.36± 1.73	4.00±0.00
Selaman & Utomo (2024)	Protein-Rich Food Waste	34.16±0.08	88.5±0.04	3.17±0.06

The VS content represents the proportion of organic matter present in a waste sample, which directly impacts the efficiency of AD and biogas production. In this study, the VS values for FW and coconut CW were recorded as 97.73% (±0.03) and 93.75% (±0.05), respectively. These values indicate that both FW and CW contain a high percentage of biodegradable organic material, making them highly suitable for biogas production through AD. According to Paranjpe et al. (2023), a higher VS value suggests a greater amount of organic matter available for microbial breakdown, which enhances biogas yield. This is because VS are composed of carbohydrates, proteins, and lipids, which serve as primary energy sources for anaerobic microorganisms. The presence of a high VS content in FW and CW suggests that these substrates have strong potential for efficient biogas recovery. Similarly, the study by de Morais Andrade et al. (2022) emphasizes that organic waste with VS content ranging from 70% to 100% is ideal for treatment under AD due to its rich organic composition. Given that both FW and CW fall within this range, they are considered excellent candidates for AD. Furthermore, comparing these findings with other studies in Table 1 reinforces the suitability of FW and CW for biogas production. Since both substrates contain a substantial proportion of biodegradable material, they can effectively undergo microbial decomposition, leading to high CH_4 production. Additionally, the slight difference between their VS values (97.73% vs. 93.75%) is not significant, suggesting that both FW and CW contribute similarly to biogas generation. By utilizing FW and CW in AD, this study supports sustainable waste management by reducing organic waste accumulation while simultaneously producing renewable energy. The high VS content of both waste types underscores their potential as valuable feedstocks for biogas recovery, further enhancing resource efficiency and environmental sustainability.

The pH level of organic waste plays a crucial role in the AD process, as it directly influences microbial activity, biogas production, and process stability. According to Yi et al. (2024), maintaining an optimal pH range is essential for ensuring efficient digestion and biogas production. The current study found that the pH values of FW and CW were 5.13 (±0.02) and 6.37 (±0.04), respectively. Although both values indicate an acidic state, they remain close to the optimal pH range of 6.8 to 7.2, which is favorable for methanogenic activity and biogas recovery. The acidic nature of FW can be attributed to its high content of fermentable carbohydrates, such as sugars and starches, which undergo rapid acidogenesis, leading to the accumulation of volatile fatty acids (VFAs) (Selaman et al., 2024). This results in a lower pH, which, if not properly regulated, could inhibit methanogenic bacteria and slow down biogas production. On the other hand, CW, which consists mainly of fibrous and lignocellulosic materials, has a slightly higher pH due to its slower degradation rate and lower VFA accumulation. The observed pH difference between FW and CW suggests that mixing digestion of both substrates could help balance the overall pH, stabilizing the digestion process and enhancing biogas yield. When compared with other studies (Table 1), the pH values reported in this study are consistent with findings from previous research, where organic wastes were also found to be in the acidic range during the initial stages of digestion. However, slight variations in pH values across studies can be attributed to differences in the composition and characteristics of waste materials, as noted by Xu et al. (2022) Factors such as substrate type, microbial community composition, buffering capacity, and inoculum-to-substrate ratio all contribute to variations in pH.

Biogas Recovery in FW, CW and mixing of (FW and CW)

Figure 2 illustrates the biogas recovery trends from the AD of FW, CW, and their mixture, demonstrating that mixing digestion achieved the highest biogas yield, peaking at 786.00 mL (±0.02) on day 8. In contrast, the highest biogas recovery from single digestion of FW and CW was 425.00 mL (±0.04) and 475.00 mL (±0.05), respectively. The observed trend revealed that biogas production increased steadily from day 1, reaching its peak on day 8, before declining significantly by day 10. This decline in biogas recovery can be attributed to the accumulation of VFAs, which lower pH levels and inhibit methanogenic bacterial activity, ultimately leading to a slowdown in the digestion process (Vidal-Antich et al., 2022; Zhang et al., 2021). The enhanced biogas production in mixing digestion can be explained by the synergistic effect between FW and CW, where the combination of these substrates promotes a more balanced carbon-to-nitrogen (C/N) ratio, microbial diversity, and enzymatic activity, leading to a more efficient digestion process (Ibro et al., 2022). FW typically contains high moisture and easily biodegradable carbohydrates, which provide an immediate source of energy for microbial activity. However, its rapid breakdown can cause excessive acid accumulation, destabilizing the process. On the other hand, CW consists of more recalcitrant lignocellulosic material, which degrades more slowly, ensuring a steady nutrient supply and buffering the pH against excessive acidification. This balance creates an optimal environment for methanogens, leading to higher biogas production compared to single digestion. Additionally, Ahuja et al. (2024) highlighted that mixing digestion improves process efficiency by supplying missing nutrients and enhancing the metabolic pathways required for microbial growth and biogas production. These findings underscore the advantages of substrate mixing in optimizing AD efficiency, increasing biogas recovery, and ensuring process stability. Furthermore, the results highlight the potential of integrating FW and CW into waste-to-energy systems, supporting sustainable waste management and renewable energy production while reducing landfill dependency and greenhouse gas emissions.

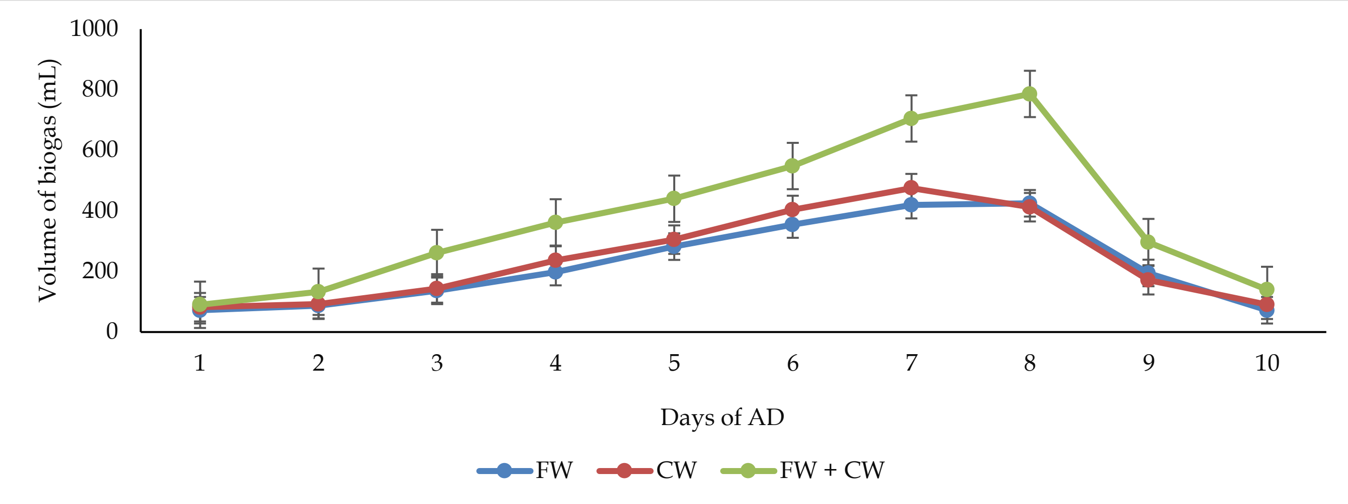

Figure 2. AD substrates (FW, CW and FW +CW) at 10 days of digestion time

Table 2. Comparison of biogas recovery from current and previous studies

References	Types of waste	Method Used	Biogas recovery (ml)
FW-CW (Current study)	Food waste & Coconut waste	Mixing digestion	786.00 mL (±0.02)
Xu et al. (2022)	Food waste & Paper waste	Mixing digestion	238.00 ±0.00
Selaman & Utomo (2024)	Protein Rich Foos Waste & Pond Sludge	Mixing digestion	120.3±0.05
Selaman et al. (2024)	Paddy husk & Dried coconut Leaves	Mixing digestion	858.0 mL (±0.05)

Table 2 presents a comparative analysis of biogas recovery between the current study and previous research, highlighting variations in AD methods and their impact on biogas yield. The data reveal that different AD techniques result in varying levels of biogas production, with mixing digestion consistently yielding the highest biogas recovery**.** This superior performance is attributed to the ability of mixing digestion to balance the nutrient composition of the substrates, thereby enhancing the overall biodegradability and efficiency of the digestion process (Ibro et al., 2022). Unlike single substrate digestion, where deficiencies in key nutrients can limit microbial growth and activity, mixing digestion ensures a more balanced carbon-to-nitrogen (C/N) ratio, which is crucial for stabilizing the metabolic pathways of anaerobic microorganisms. Furthermore, combining different organic wastes can increase microbial diversity and enhance enzymatic activity, leading to improved breakdown of complex organic matter and greater methane production (Chrispim et al., 2021).

Another important factor contributing to the enhanced performance of mixing digestion is its ability to dilute and mitigate inhibitory substances, such as ammonia (NH_3) or volatile fatty acids (VFAs), which might otherwise accumulate and inhibit microbial activity in single substrate digestion (Vidal-Antich et al., 2022). The observed variability in biogas recovery across different studies suggests that factors such as substrate composition, inoculum type, digestion temperature, retention time, and reactor design all play a crucial role in determining AD efficiency. Additionally, external conditions such as pH levels, microbial adaptation, and pre-treatment methods can significantly impact biogas yield. Study by Selaman & Utomo (2024) further emphasize that optimizing feedstock combinations and operational parameters is essential to maximizing biogas production, ensuring process stability, and improving energy recovery from organic waste. These findings highlight the importance of tailoring AD systems to specific waste compositions to achieve higher biogas output, enhanced waste reduction, and more efficient renewable energy generation.

Conclusion

Based on the research findings and discussion, it can be concluded that the level of learning independence among Class XI MIPA students at SMAN 6 Mataram during the 2020/2021 academic year in chemistry during the COVID-19 pandemic was categorized as moderate, with an average score of 61.91. Similarly, students' chemistry learning outcomes, based on the average score of 72.17, were also classified as moderate. Furthermore, there was a positive and significant relationship between learning independence and chemistry learning outcomes among Class XI MIPA students at SMAN 6 Mataram during the COVID-19 pandemic in the 2020/2021 academic year. Based on the conducted research, the researcher proposes several recommendations. First, teachers are encouraged to continuously support and foster students' learning independence by implementing engaging teaching methods to enhance learning outcomes. Second, future researchers are advised to explore other variables that may influence students' chemistry learning outcomes. Lastly, researchers should consider students' characteristics and other factors that may affect both learning independence and academic performance.

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Author Contributions
The research was conceptualized by Authors R. S., D. N. H., M. F. A., A. J and A. L. The methodology, data analysis, and manuscript writing were conducted by Authors R. S., D. N. H., M. F. A., while Author A. L., contributed to the review and supervision of the study.

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Conflicts of Interest
The authors declare no conflict of interest.

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