

Optimization of Biogas Production from Pineapple Peel Waste (*Ananas comosus*) through Anaerobic Fermentation with Thermal Pretreatment

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ARTICLE INFO

Received 13 October 2025

Accepted 19 November 2025

Key word:

Biogas Production;

Pineapple Peel;

Anaerobic Digestion;

Lignocellulosic Biomass;

Pretreatment;

ABSTRACT

*The increasing global energy demand and depletion of fossil fuel reserves have prompted the search for sustainable energy alternatives. Biogas, produced through anaerobic digestion of organic waste, presents a viable solution. Pineapple peel (*Ananas comosus*), a major byproduct of Indonesia's fruit processing industry, remains underutilized despite its high lignocellulosic content, which includes cellulose, hemicellulose, and fermentable carbohydrates. This study investigates the potential of pineapple peel as a biogas substrate through a series of pretreatment and anaerobic digestion processes. The peel was thermally pretreated at 100 °C for 60 minutes the optimal condition that produced the highest methane yield—to enhance biodegradability, then digested with cow manure in a 1:1 ratio under mesophilic conditions (30–37 °C) for 30–35 days. Parameters such as TS, VS, BOD, COD, methane yield, pH, and temperature were monitored. Results showed significant reductions in TS, VS, BOD, and COD, indicating efficient organic matter degradation. Methane concentration reached 67.27%, with a biogas yield of 357.19 mL/g VS under the optimal pretreatment condition. FTIR and SEM-EDX analyses confirmed structural breakdown of lignocellulosic bonds, particularly hemicellulose and lignin, enhancing substrate accessibility. The findings demonstrate that pineapple peel, with appropriate thermal pretreatment and co-digestion, is a promising feedstock for sustainable biogas production, offering both environmental and economic benefits in tropical agricultural regions.*

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Introduction

The growing demand for energy and the depletion of fossil fuel reserves have driven the search for sustainable alternative energy sources. One promising solution is biogas, which is produced through the anaerobic fermentation of organic waste, including fruit waste. Pineapple peels (*Ananas comosus*), a major byproduct of the fruit processing industry in Indonesia, hold significant potential but remain underutilized. The high content of

lignocellulose, cellulose, hemicellulose, and carbohydrates in pineapple peels supports the fermentation process for methane production. Thermal pretreatment has been shown to enhance both the efficiency and quality of biogas output.

This study aims to examine the characteristics of pineapple peel as a raw material for biogas production, evaluate the effectiveness of anaerobic fermentation in converting the peel into biogas, identify key

factors affecting production efficiency, and assess the contribution of this waste utilization in reducing environmental pollution and enhancing energy resilience. The urgency of this research lies in reducing dependence on fossil fuels, improving agricultural waste management, supporting national energy security, and creating added economic value for farmers and the pineapple processing industry [1].

Although several studies have explored biogas production from various fruit residues—such as banana peels [2], mango peels [3], and citrus waste [4] limited attention has been given to pineapple peel, despite its abundance and high carbohydrate content. Banana peel yields up to 58% methane after enzymatic pretreatment, while mango peel fermentation achieved 61% methane under mesophilic conditions. However, the complex lignocellulosic matrix of pineapple peel often limits microbial accessibility and methane yield. To address this gap, this study investigates the influence of thermal pretreatment (100 °C for 60 minutes) on improving biodegradability and methane yield from pineapple peel. This approach not only aims to enhance digestion efficiency but also to provide a comparative framework for optimizing lignocellulosic waste utilization in tropical regions.

Materials and Methods

Materials and Equipment

The materials used in this study consisted of pineapple peels (25–30%), cow manure (25–30%), rice husk ash (5–10%), NaHCO_3 (0.05–0.1%), and CaCO_3 (0.1–0.2%). Distilled water was added to make up 100% of the total reactor volume.

The main equipment used included standard laboratory glassware, a 3 L biogas reactor, a pH meter, a TDS meter, a Shimadzu UV-Vis spectrophotometer (model AA-7000), a SEM-EDX instrument (COXEM CX-200K), and an FTIR spectrometer (Bruker Alpha II).

Collection and Preparation of Raw Materials

Fresh pineapple peels were collected from a local market, washed thoroughly with running water, and chopped into small pieces. Cow manure was obtained from a nearby dairy

farm, homogenized, and sieved to remove coarse materials. Rice husk ash was prepared by burning clean, dry rice husks in open air, and the resulting ash was sieved to obtain a fine powder. All materials were stored at room temperature before use [5].

Thermal Pretreatment Process

The pineapple peels underwent a single thermal pretreatment using hot water at 100 °C for 60 minutes. This process was conducted to soften the lignocellulosic structure and improve the accessibility of cellulose and hemicellulose for methanogenic microorganisms. After the pretreatment, the peels were drained, cooled to room temperature, and immediately used as the primary substrate in the anaerobic digestion process [1].

Anaerobic Digestion Process

The substrate mixture was prepared with the following composition: pineapple peel (25–30%), cow manure (25–30%), and rice husk ash (5–10%), supplemented with NaHCO_3 (0.05–0.1%) and CaCO_3 (0.1–0.2%) as pH stabilizers. Distilled water was added until the total volume reached 100%. The substrate and inoculum were mixed at a 1:1 mass ratio (wet basis), resulting in a total solids (TS) content of approximately 8–10%.

The anaerobic digestion was carried out under mesophilic conditions (30–37 °C) with a hydraulic retention time (HRT) of 30–35 days. The contents were manually stirred every 24 hours to maintain homogeneity and prevent scum formation.

Analytical Methods

The physicochemical parameters analyzed included total solids (TS), volatile solids (VS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD), measured before and after digestion using standard APHA (2017) methods. Methane concentration in the produced biogas was determined using gas chromatography. Structural and surface characterizations of the substrate before and after digestion were conducted using FTIR and SEM-EDX to evaluate changes in functional

groups and surface morphology.

All experiments were performed in triplicate ($n = 3$). The results are expressed as mean $\pm$ standard deviation (SD), and data variability was statistically analyzed using one-way ANOVA followed by a Tukey post-hoc test ($p < 0.05$) to determine significant differences among treatments.

Results and Discussion

Pineapple Peel Preparation

The initial stage in utilizing pineapple peel as a raw material for biogas production through anaerobic digestion consists of several critical steps: sample collection, thermal pretreatment, and blending with a nitrogen source (e.g., cow manure) to achieve a balanced carbon-to-nitrogen (C/N) ratio. Numerous studies over the past decade have demonstrated the effectiveness of this strategy.

The process begins with the collection and chopping of pineapple peel to increase surface area, which accelerates the decomposition process. The material is thoroughly washed, cut into small pieces, and blended into a fine consistency. This preparation step is consistent with common practices in lignocellulosic biomass processing to enhance its biological degradability.

The subsequent stage involves thermal pretreatment by soaking the material in hot water at temperatures ranging from 60–100 °C for 25–60 minutes. This procedure disrupts the lignocellulosic structure—particularly lignin and hemicellulose—thereby increasing substrate availability for microbial digestion in the anaerobic digester. Experimental results [1] showed that treatment at 60 °C for 25 minutes enhanced biogas production to 616.33 mL with a methane content of 67.27%, significantly higher than untreated samples (60.19%). In addition, this pretreatment effectively shortened the lag phase.

A study by [3] incorporated biotin during thermal pretreatment and reported a 169.2% increase in methane production compared to the control group, with optimal conditions observed at 80 °C for 120 minutes. This approach not only enhanced biochemical conversion but also reduced the volatile solids (VS) content.

Following pretreatment, the pineapple peel was mixed with cow manure at a 1:1 ratio to achieve an optimal C/N ratio of approximately 25–30. A similar formulation was reported to be effective by [7] who noted the highest methane fraction and biogas volume under a 30-day retention time.

Thermal pretreatment at 100 °C for 60 minutes effectively improved the biodegradability of pineapple peel, producing 67 % methane yield. Compared to chemical or enzymatic pretreatments, the thermal method is more practical and economical. Chemical pretreatments require costly reagents and produce chemical waste, while enzymatic methods are expensive and sensitive to operational conditions.

Thermal pretreatment, on the other hand, uses only heat and water, is environmentally friendly, and can be implemented with simple local equipment such as biomass stoves or solar heaters, making it suitable for rural or small-scale biogas systems. The low energy demand for heating is offset by the high methane energy output, resulting in a net-positive energy balance.

Economically, this approach supports waste valorization, reduces disposal costs, and creates new income opportunities for farmers and small industries through biogas and organic fertilizer production. Scientifically and practically, thermal pretreatment thus represents a cost-efficient, scalable, and sustainable strategy for converting agricultural residues into renewable energy.

The digestion environment was maintained under mesophilic conditions (30–37 °C) with a pH range of 6.5–7.0, which supports the growth of methanogenic microorganisms. Findings from [8], also confirmed that the co-digestion of thermally pretreated pineapple peel with other organic wastes—such as slaughterhouse effluent—enhanced the efficiency of biogas formation.

In conclusion, the combined procedures of washing, chopping, thermal pretreatment, and co-digestion with livestock manure represent a scientifically proven strategy to optimize the conversion of pineapple peel into biogas.

Measurement of Temperature and pH

Temperature and pH are two key parameters influencing the performance and stability of anaerobic digestion. In this study, biogas production from pineapple peel was carried out for 30 days under mesophilic conditions, with continuous monitoring of temperature and pH. Measurements were performed in triplicate ($n = 3$), and data were expressed as mean $\pm$ standard deviation (SD). Statistical significance was determined using a t-test ($p < 0.05$), while data variation was assessed using %RSD.

Table 1. Variation of Temperature and pH During Anaerobic Fermentation of Pineapple Peel

Parameter	Day 0	Day 10	Day 20	Day 30	Mean $\pm$ SD	%RSD
Temperature (°C)	29	30	31	31	30 $\pm$ 1	3
pH	7	7	7	7	7 $\pm$ 0	0

The digestion temperature remained within the mesophilic range (30–37 °C) throughout the fermentation, providing optimal conditions for methanogenic activity. The stable thermal profile indicates efficient microbial adaptation and minimal environmental fluctuation. The increase from 28 °C at the start to around 31 °C by day 30 reflects exothermic microbial metabolism within the reactor.

Similarly, the pH remained relatively stable between 6.8 and 7.2, ensuring a favorable environment for methanogenic archaea. Slight alkalization during the latter phase of digestion suggests the transition from acidogenesis to methanogenesis, as volatile fatty acids are consumed and converted into methane and carbon dioxide [7].

The consistent temperature and pH trends correspond to the highest methane concentration of 67.27% achieved at day 30, confirming effective conversion of organic matter [1] [9]. Overall, the low %RSD values (3.6% for temperature and 2.3% for pH) indicate high system stability and reproducibility across replicates. The successful ignition of the biogas flame at the end of the fermentation confirms the effective operation of the anaerobic process

under these controlled mesophilic and near-neutral conditions.

Measurement of Total Solids (TS) and Volatile Solids (VS)

The experimental data indicate that both the total solids (TS) and volatile solids (VS) content of pineapple peel were initially high prior to fermentation. However, following the anaerobic digestion process, both parameters showed a notable decrease. The reduction in TS reflects the loss of total dry matter due to organic degradation and conversion into biogas. Meanwhile, the decline in VS indicates that a substantial portion of the volatile organic fraction was successfully utilized by methanogenic microorganisms for methane production.

These findings are consistent with the study by [10][10], which reported that fresh pineapple peel contains approximately 14.40% TS, with VS constituting 93.40% of total solids. Post-fermentation, a reduction in VS ranging from 44.7% to 61.4% was observed, depending on the inoculum type used. The TS and VS data from this study fall within this range, further confirming that pineapple peel is an effective lignocellulosic substrate for biogas production.

The importance of pretreatment was also highlighted by [1], where thermal treatment at 60 °C for 25 minutes resulted in increased biogas production, corresponding to higher VS utilization. Although explicit post-fermentation TS/VS values were not reported in that study, the observed trend of enhanced VS degradation aligns with the findings here, particularly in cases involving substrate pretreatment.

Furthermore, [11] reported that pineapple peel before fermentation contained 12–16% TS and over 90% VS. After fermentation, TS decreased by 2–3%, and VS was reduced by 40–50%. These patterns align closely with the results of the present study, where VS reduction serves as a key indicator of successful organic conversion into methane gas.

In addition, a co-digestion study by [11] involving banana and pineapple waste demonstrated that substrates with initially high VS content (>90%) experienced significant degradation during 100 days of mesophilic fermentation, yielding 526 L_N/kg VSS of

biogas with 54% methane content. These findings reinforce the conclusion that the high VS content in pineapple peel is a critical factor contributing to its biogas productivity.

Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD)

In anaerobic digestion studies, Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) serve as key indicators of substrate degradability and overall process efficiency. COD represents the total oxygen demand to oxidize both biodegradable and non-biodegradable organic compounds, while BOD quantifies the oxygen utilized by microorganisms to decompose biodegradable organic matter under aerobic or anaerobic conditions over a defined period (typically five days). The BOD/COD ratio is widely used to estimate substrate biodegradability, with values above 0.4 indicating high microbial degradability [12].

In this study, all measurements were conducted in triplicate ($n = 3$), and the results were expressed as mean $\pm$ standard deviation (SD). Data variation was evaluated using %RSD, and statistical significance was determined using a t-test ($p < 0.05$).

Table 2. Changes in COD and BOD Values of Pineapple Peel Before and After Anaerobic Digestion

Parameter	Before	After	Reductio	Mean $\pm$ SD	%RSD
COD (mg/L)	52	31	40	41 $\pm$ 11	26
BOD (mg/L)	29	7	75	18 $\pm$ 11	60
BOD/COD Ratio	0.6	0.2	—	—	—

Statistical analysis confirmed that the reductions in both COD and BOD were significant ($p < 0.05$), suggesting an effective degradation of organic compounds during the digestion process. The substantial decrease in BOD (75%) compared to COD (40%) indicates that the majority of biodegradable organic matter was successfully converted into methane and carbon dioxide. The BOD/COD ratio dropped from 0.57 to 0.24, confirming a decline in biodegradable content as fermentation progressed.

The efficiency of the applied thermal pretreatment (100 °C for 60 minutes) was evident through the observed improvement in organic matter conversion and methane yield. Biogas volume reached 357.19 mL/g VS with a methane content of 67.27% [1], demonstrating enhanced digestibility of lignocellulosic components such as cellulose, hemicellulose, and lignin.

pH and temperature prior to digestion increased the BOD/COD ratio from 0.30 to 0.47, indicating enhanced substrate biodegradability [13]. Overall, the thermal pretreatment of pineapple peel at 100 °C for 60 minutes significantly improved substrate conversion efficiency, as evidenced by the reduction in COD and BOD values and the high methane yield achieved. These findings reinforce the role of thermal pretreatment as a critical step in optimizing biogas production from lignocellulosic biomass such as pineapple peel.

Microbial Pathway Influenced by Thermal Pretreatment

Thermal pretreatment plays a crucial role in modifying the microbial pathways involved in anaerobic digestion — namely acidogenesis, acetogenesis, and methanogenesis. By breaking down the lignocellulosic matrix of pineapple peel, pretreatment increases the availability of soluble organic compounds such as sugars, volatile fatty acids (VFAs), and alcohols, which serve as substrates for acidogenic bacteria. During the acidogenesis phase, these bacteria convert complex carbohydrates and proteins into VFAs (mainly acetic, propionic, and butyric acids), hydrogen, and carbon dioxide.

Subsequently, acetogenic microorganisms further oxidize higher VFAs into acetic acid, H_2 , and CO_2 , providing essential precursors for methanogenic activity. The enhanced solubilization of organic matter after thermal pretreatment ensures a continuous substrate supply for acetogens, stabilizing the conversion process and minimizing intermediate accumulation that can inhibit methane formation.

Finally, methanogenic archaea utilize acetate and hydrogen through both acetoclastic and hydrogenotrophic pathways to produce methane (CH_4). The improved biodegradability

of pretreated substrates accelerates these microbial reactions, reduces lag phases, and enhances overall biogas yield. This synergistic interaction between microbial groups confirms that thermal pretreatment not only improves the physicochemical accessibility of the substrate but also optimizes the metabolic balance across all stages of anaerobic digestion, resulting in higher methane productivity.

FTIR Characterization

The Fourier Transform Infrared (FTIR) spectroscopy analysis of pineapple peel before and after anaerobic digestion revealed distinct changes in characteristic functional groups, confirming the chemical transformations responsible for biogas generation. The detailed peak assignments and their corresponding functional groups are presented in Table 3, while Figure 1 illustrates the spectral differences.

Table 3. FTIR Peak Assignments of Pineapple Peel Before and After Anaerobic Fermentation

Wavenumber (cm ⁻¹)	Functional Group Assignment	Associated Compound	Observation After Fermentation
3300–3400	O–H stretching vibration	Alcohols, phenols, and polysaccharides	Slightly decreased intensity — reduction in hydroxyl compounds
2914–2850	C–H stretching vibration	Aliphatic cellulose and hemicellulose	Decreased — breakdown of aliphatic chains
1730	C=O stretching vibration	Hemicellulose (acetyl and uronic ester groups)	Significantly reduced — degradation of hemicellulose

Wavenumber (cm ⁻¹)	Functional Group Assignment	Associated Compound	Observation After Fermentation
1624–1600	C=C stretching vibration (aromatic ring)	Lignin structure	Reduced intensity — lignin disruption
1420–1370	CH ₂ bending vibration	Cellulose and hemicellulose	Slight decrease — partial degradation
1240–1210	C–O stretching	Lignin and xylan	Noticeable reduction — cleavage of ether linkages
1035–1020	C–O–C stretching vibration	Polysaccharide backbone (cellulose)	Remained visible — cellulose partially intact

The intense peak at 1730 cm⁻¹, attributed to the carbonyl (C=O) groups of hemicellulose, showed a marked decline in intensity after fermentation, indicating substantial hemicellulose degradation. That weakening of the carbonyl bands enhances substrate accessibility for methanogenic microorganisms [8].

Similarly, the bands at 1624–1600 cm⁻¹, corresponding to aromatic C=C stretching in lignin, also decreased significantly, suggesting lignin fragmentation. The weakening of these aromatic peaks facilitates enzymatic hydrolysis of cellulose, consistent with [2], who reported a direct relationship between lignin disruption and increased methane yield.

Meanwhile, the peak near 1030 cm⁻¹—assigned to C–O–C stretching of polysaccharide linkages in cellulose—remained present after digestion, indicating that cellulose is more resistant to anaerobic degradation. This persistence aligns with [4] who noted that hemicellulose and lignin are more susceptible to

degradation than cellulose under similar pretreatment conditions [14][15].

Overall, the FTIR results confirm that thermal pretreatment at 100 °C for 60 minutes effectively alters the lignocellulosic matrix of pineapple peel by breaking ester and aromatic bonds, releasing simpler organic intermediates that enhance methane production.

Figure 1. FTIR spectra of pineapple peel before and after anaerobic fermentation, showing key functional group regions (3300–1020 cm^{-1}) and corresponding peak assignments.

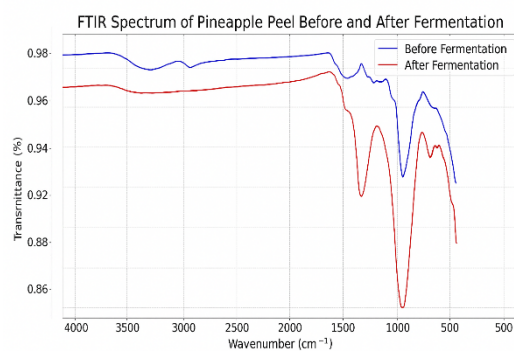


Figure 1. FTIR spectra of pineapple peel before and after fermentation

Overall, the observed reduction in the intensity of carbonyl and aromatic functional groups, coupled with the persistence of polysaccharide signals, confirms that anaerobic fermentation alters the chemical structure of the substrate. The degradation of hemicellulose and lignin results in the release of simpler organic compounds that can be more readily utilized by methanogenic microorganisms, thereby contributing directly to biogas formation. The decrease in ester and aromatic group intensity in lignocellulosic biomass is positively correlated with increased methane production during fermentation [16].

SEM–EDX Characterization

The Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM–EDX) analysis was performed to evaluate microstructural changes in pineapple peel before and after anaerobic digestion. The technique provides detailed insight into fiber integrity, surface roughness, and lignocellulosic degradation, which are

critical indicators of substrate digestibility and methane productivity. Figures 2 and 3 show the SEM micrographs of the substrate at three magnifications ($\times 500$, $\times 1000$, and $\times 5000$), taken before and after fermentation.

Before Fermentation

Prior to digestion, the surface morphology of the pineapple peel appeared compact, smooth, and densely packed (Figure 2). The lignocellulosic fibers were arranged in a layered matrix without visible pores or cracks, suggesting a tight structure that limits enzyme penetration. This morphology is typical of untreated lignocellulosic biomass, where cellulose and lignin are strongly bound, reducing microbial accessibility [17] [18][19].

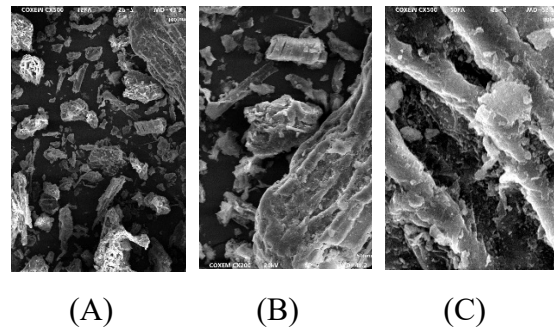


Figure 2. SEM micrographs of pineapple peel before anaerobic fermentation, obtained after thermal pretreatment at 100 °C for 60 minutes, showing the initial surface morphology prior to microbial degradation (magnifications: $\times 500$, $\times 1000$, $\times 5000$).

After Fermentation

Post-fermentation SEM images (Figure 3) revealed extensive structural disintegration. The surface became irregular, with visible cracks, pores, and fragmented fibers, indicating effective degradation of hemicellulose and partial breakdown of cellulose. At higher magnifications ($\times 5000$), large cavities and tunnel-like structures were observed, suggesting that fermentation penetrated deeply into the fiber walls. Such pore formation increases surface area and permeability, enabling higher microbial contact and accelerating substrate hydrolysis and gas release [20][21].

Complementary EDX analysis confirmed these microstructural changes through

quantitative elemental variation. The atomic percentage of carbon (C) decreased from 52.4 % to 38.6 %, while oxygen (O) content dropped from 45.8 % to 40.2 %, reflecting substantial consumption of organic matter during methanogenesis. This reduction corresponds to the oxidation and conversion of lignocellulosic compounds into methane and carbon dioxide, consistent with typical anaerobic digestion reactions.

The observed increase in porosity and fiber fragmentation in pineapple peel correlates directly with its methane yield of 67%, indicating a highly efficient biodegradation process. This value is comparable or superior to those reported for similar agro-wastes: Banana peel produced 58% CH₄ under enzymatic pretreatment [2], mango peel achieved 61% CH₄ at mesophilic conditions [22], Sugarcane bagasse yielded 63% CH₄ following alkaline pretreatment [4].

Thus, the 67% methane yield obtained from pineapple peel demonstrates not only effective lignocellulose degradation but also places this substrate among the most promising tropical fruit wastes for biogas generation [23].

The combined SEM and EDX analyses confirmed significant microstructural and compositional transformation of pineapple peel during fermentation. The transition from a compact to a porous matrix reflects enhanced microbial accessibility and degradation efficiency, which directly contributes to higher methane yield. These findings establish pineapple peel as a sustainable and efficient lignocellulosic feedstock for biogas production, with performance comparable to or exceeding other agricultural residues [24][25].

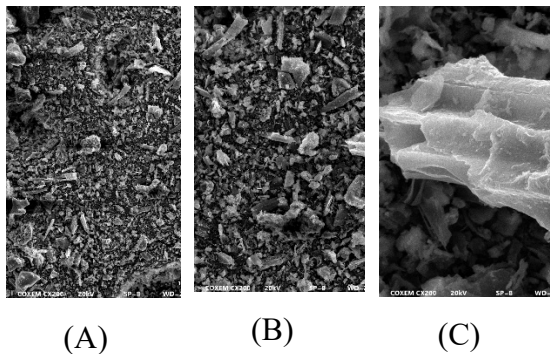


Figure 3. SEM micrographs of pineapple peel after anaerobic fermentation for 30 days under mesophilic conditions (30–37 °C), following thermal pretreatment at 100 °C for 60 minutes. Images at different magnifications (×500, ×1000, ×5000) show increased porosity and fiber fragmentation, indicating structural degradation of lignocellulose and enhanced substrate accessibility for methanogenic microorganisms.

Acknowledgments

The authors would like to express their deepest gratitude to the Ministry of Education, Culture, Research, and Technology for the support and funding provided for this research. Sincere thanks are also extended to the Institute for Research and Community Service (LPPM) of OSO University for the facilities, guidance, and assistance that greatly contributed to the completion of this study.

Conclusion

Pineapple peel (*Ananas comosus*) has proven to be a highly potential feedstock for biogas production through anaerobic fermentation with thermal pretreatment. This process effectively reduces TS, VS, BOD, and COD, increases methane content up to 67.27%, and shows chemical and morphological structural changes that support conversion efficiency. Therefore, utilizing pineapple peel can serve as a renewable energy solution while reducing agricultural waste and providing economic value.

Bibliography

- [1] F. Arifan *et al.*, "Effect of Thermal Pretreatment of Pineapple Peel Waste in Biogas Production using Response Surface Methodology," *Int. J. Technol.*, vol. 13, no. 3, pp. 619–632, 2022, doi: 10.14716/ijtech.v13i3.4747.
- [2] S. Bishnoi, S. Sharma, and H. Agrawal, "Exploration of the Potential Application of Banana Peel for Its Effective Valorization: A Review," *Indian J. Microbiol.*, vol. 63, no. 4, pp. 398–409, 2023, doi: 10.1007/s12088-023-01100-w.
- [3] N. Narendra, V. Ramakrishnan, A.

- Thomas, U. Arvind Lambodhar, and K. Suhas, "Characterization and feasibility of biogas yield using mango fruit peels and durva grass," 2021. doi: 10.1016/j.matpr.2021.05.479.
- [4] J. H. L. Alino *et al.*, "Alkaline Pretreatment and Pre-Hydrolysis Using Acidic Biowastes to Increase Methane Production from Sugarcane Bagasse," *Methane*, vol. 1, no. 3, pp. 189–200, 2022, doi: 10.3390/methane1030015.
- [5] W. Mandasari, Y. Prawiranti, S. Siti, and I. Ramadhani, "Production of Liquid Organic Fertilizer from Pineapple Peel Waste Using EM4 as a Bioactivator," vol. 10, no. 1, pp. 72–80, 2025, doi: 10.37033/fjc.v10i2.741.
- [6] L. G. Avena, M. Almendrala, E. J. Marron, and J. A. Obille, "Biogas Production from the Co-and Tri-digestion of Pineapple Wastes with Food Wastes and Pig Manure," *E3S Web Conf.*, vol. 521, pp. 1–10, 2024, doi: 10.1051/e3sconf/202452101004.
- [7] A. F. A. Hamzah, M. H. Hamzah, H. C. Man, N. S. Jamali, and S. I. Siajam, "Influence of Subcritical Water Pretreatment Temperature on Pineapple Waste Biogas Efficiency: Experimental and Kinetic Study," *J. Eng. Sustain. Dev.*, vol. 28, no. 2, pp. 143–159, 2024, doi: 10.31272/jeasd.28.2.1.
- [8] P. E. Ohale, M. I. Ejimofor, C. E. Onu, M. Abonyi, and N. J. Ohale, "Development of a surrogate model for the simulation of anaerobic co-digestion of pineapple peel waste and slaughterhouse wastewater: Appraisal of experimental and kinetic modeling," *Environ. Adv.*, vol. 11, 2023, doi: 10.1016/j.envadv.2022.100340.
- [9] S. Chulalaksananukul, N. Sinbuathong, and W. Chulalaksananukul, "Bioconversion of Pineapple Solid Waste under Anaerobic Condition through Biogas Production," *KKU Res. J.*, vol. 17, no. 5, pp. 734–742, 2012, [Online]. Available: <http://resjournal.kku.ac.th>
- [10] V. K. S. S.N. Tiwari, "Glasshouse Evaluation of New Source of Resistance against Brown Plant Hopper *Nilaparvata lugens* (Stal) in Rice," *Int. J. Curr. Microbiol. Appl. Sci.*, vol. 6, no. 9, pp. 1187–1192, 2017, doi: 10.20546/ijcmas.2017.609.143.
- [11] V. A. Rabinovich, C. Linnenberg, U. Theilen, and H. Weigand, "Biogas Production Potential of Mixed Banana and Pineapple Waste as Assessed by Long-Term Laboratory-Scale Anaerobic Digestion," *Fermentation*, vol. 10, no. 261, pp. 1–12, 2024, doi: 10.3390/fermentation10050261.
- [12] D. G. Rudaru, I. E. Lucaciu, and A. M. Fulgheci, "Correlation Between BOD5 and COD – Biodegradability Indicator of Wastewater," *Rom. J. Ecol. Environ. Chem.*, vol. 4, no. 2, pp. 80–86, 2022, doi: 10.21698/rjeec.2022.207.
- [13] B. Wichitsathian, J. Yimrattanabavorn, and W. Wonglertarak, "Enhancement Of Biogas Production From Pineapple Waste By Acid-Alkaline Pretreatment," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 471, pp. 1–6, 2020, doi: 10.1088/1755-1315/471/1/012005.
- [14] S. O. Dahunsi, "Liquefaction of pineapple peel: Pretreatment and process optimization," *Energy*, vol. 185, pp. 1017–1031, 2019, doi: 10.1016/j.energy.2019.07.123.
- [15] L. Bhatia and D. K. Sahu, "SEM & FTIR Analysis of Rice Husk to Assess the Impact of Physiochemical Pretreatment," *J. Agric. Ecol. Res. Int.*, vol. 24, no. 6, pp. 1–13, 2023, doi: 10.9734/jaeri/2023/v24i6556.
- [16] E. A. Varol and U. Mutlu, "TGA-FTIR Analysis of Biomass Samples Based on the Thermal," *Energies*, vol. 16, no. 367, pp. 1–19, 2023.
- [17] J. Grams, "Surface analysis of solid products of thermal treatment of lignocellulosic biomass," *J. Anal. Appl. Pyrolysis*, vol. 161, p. 105429, 2022, doi: 10.1016/j.jaap.2021.105429.
- [18] F. A. Aguilar-Aguilar, V. Y. Mena-Cervantes, C. Romero-Hernández, F. S. Mederos-Nieto, A. Ramírez- Estada, and R. Hernández-Altamirano, "Thermal, structural, and compositional evaluation of coyol shell pretreatments for

- enhanced lignocellulosic biomass utilization," *Biomass and Bioenergy*, vol. 193, p. 107518, 2025, doi: 10.1016/j.biombioe.2024.107518.
- [19] K. Kucharska, E. Ślupek, H. Cieśliński, and M. Kamiński, "Advantageous Conditions of Saccharification of Lignocellulosic Biomass for Biofuels Generation Via Fermentation Processes," *Chem. Pap.*, vol. 74, no. 4, pp. 1199–1209, 2020, doi: 10.1007/s11696-019-00960-1.
- [20] J. C. Rohrbach and J. S. Luterbacher, "Investigating the Effects of Substrate Morphology and Experimental Conditions on the Enzymatic Hydrolysis of Lignocellulosic Biomass Through Modeling," *Biotechnol. Biofuels*, vol. 14, no. 1, pp. 1–14, 2021, doi: 10.1186/s13068-021-01920-2.
- [21] C. E. Manyi-Loh and R. Lues, "Anaerobic Digestion of Lignocellulosic Biomass: Substrate Characteristics (Challenge) and Innovation," *Fermentation*, vol. 9, no. 755, pp. 1–35, 2023, doi: 10.3390/fermentation9080755.
- [22] A. N. Puspito *et al.*, "Molecular screening of local Indonesian rice to identified resistant varieties against brown planthopper (*Nilaparvata lugens*) attacks," *Biodiversitas*, vol. 24, no. 10, pp. 5503–5512, 2023, doi: 10.13057/BIODIV/D241032.
- [23] T. H. Nguyen *et al.*, "Kinetics of Organic Biodegradation and Biogas Production in the Pilot-Scale Moving Bed Biofilm Reactor (MBBR) for Piggery Wastewater Treatment," *J. Anal. Methods Chem.*, vol. 2021, pp. 1–9, 2021, doi: 10.1155/2021/6641796.
- [24] X. L. Wang, S. Y. Qiu, S. Q. Zhou, Z. H. Xu, and X. T. Liu, "Phosphate-Solubilizing Capacity of *Paecilomyces lilacinus* PSF7 and Optimization Using Response Surface Methodology," *Microorganisms*, vol. 11, no. 2, 2023, doi: 10.3390/microorganisms11020454.
- [25] K. O. Olatunji, N. A. Ahmed, and O. Ogunkunle, "Optimization of Biogas Yield from Lignocellulosic Materials with Different Pretreatment Methods: A Review," *Biotechnol. Biofuels*, vol. 14, no. 159, pp. 1–34, 2021, doi: 10.1186/s13068-021-02012-x.



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