JPPIPA 12(4) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

The Potential of Corn Cobs for Bio-CNG Production and Fermented Feed, and Circular System Marketing to Support a Residue-Free Circular Economy

Mimin Aminah[1*], Rindang[1], ST Risyahadi[2], B Purwanto[3], Dian Anggraeni[4], HB Surbakti[5], Suryahadi[6], Gelar Satya Budhi[7]

[1] Department of Management, Faculty of Economics and Management, IPB University, Indonesia.
[2] Department of Nutrition and Feed Technology, Faculty of Animal Science, IPB University, Indonesia.
[3] Vocational School, IPB University, Indonesia.
[4] Department of Animal Nutrition and Feed Technology, Faculty of Animal Science, IPB University, Indonesia.
[5] Faculty of Animal Science, IPB University, Indonesia.
[6] Tropical Animal Research Center, IPB University, Indonesia.
[7] Center for Sustainable Food Crop Agricultural Land Study, Bogor, Indonesia.

Received: February 15, 2026
Revised: March 13, 2026
Accepted: April 25, 2026
Published: April 30, 2026

Corresponding Author:
Mimin Aminah
mimin@apps.ipb.ac.id

DOI: 10.29303/jppipa.v12i4.14604

Abstract: The increasing volume of corn cob waste in Indonesia poses environmental challenges and reflects underutilized biomass with potential economic value. This study examines the conversion of corn cobs into Bio-CNG through anaerobic digestion and the utilization of fermentation residues as livestock feed within a circular economy framework. The novelty lies in integrating energy production, feed generation, and circular system marketing in a single agro-based model. A laboratory experimental study using a 3×3 factorial Completely Randomized Design (CRD) was conducted, employing Biomethane Potential Tests (BMP) with rumen and methanogenic inoculums at different temperatures and fermentation times (2–6 days). Gas production and digestate composition were analyzed using standard methods, including proximate analysis. Results show substrate degradation up to 55.34%, methane production reaching 3.82% (rumen microbes, 39°C) and 10.79% (methanogenic basis), and total gas production up to 10.29%. Digestate quality improved, with protein increasing from 4.95% to 7.39% and TDN from 53.34% to 55.42%, indicating suitability as ruminant feed. The study is limited to laboratory-scale and short fermentation duration. Practically, this model can support integrated agroenergy systems in rural areas. In conclusion, corn cobs offer significant potential as a dual resource for renewable energy and livestock feed, supporting sustainable circular agriculture.

Keywords: Anaerobic digestion; Bio-CNG; Biogas; Circular economy; Corn cobs fermentation; Livestock feed

Introduction

Indonesia is currently facing a significant challenge in managing agricultural waste sustainably, in line with increasing agricultural production and the resulting rise in organic waste volumes (Apriyelita & Marviano, 2025). Corn cobs, as one of the most abundant agricultural residues, remain largely underutilized and are often left to decay or burned, contributing to greenhouse gas emissions and environmental degradation (Manzini et al., 2024; IPCC, 2019). At the same time, rural areas continue to face structural constraints in accessing affordable energy and maintaining a stable supply of livestock feed. This situation creates an urgent need for integrated solutions that not only reduce waste but also generate economic value and support rural resilience.

If not properly managed, agricultural and agro-industrial waste such as palm oil residues can pose

---

How to Cite:
Aminah, M., Rindang, Risyahadi, R., Purwanto, B., Anggraeni, D., Surbakti, H., … Budhi, G. S. (2026). The Potential of Corn Cobs for Bio-CNG Production and Fermented Feed, and Circular System Marketing to Support a Residue-Free Circular Economy. *Jurnal Penelitian Pendidikan IPA*, *12*(4), 770–782. https://doi.org/10.29303/jppipa.v12i4.14604

environmental risks; however, when utilized effectively, they can serve as valuable resources rich in essential nutrients and significantly improve productivity and soil quality (Hayati et al., 2025).

The circular economy concept offers a strategic framework to address these challenges by transforming waste into valuable resources through reuse, recycling, and valorization (Geissdoerfer et al., 2017; Velenturf & Purnell, 2021; Arisena & Pradnyandari, 2026; Rahman, 2019). In this context, the utilization of corn cobs as feedstock for anaerobic digestion represents a promising pathway to produce renewable energy while minimizing environmental impacts. Corn cobs are rich in lignocellulosic materials, making them suitable for biogas production, although their conversion efficiency depends on process optimization and microbial activity (Manyi-Loh & Lues, 2023; Zou et al., 2020; Appels et al., 2008).

Previous studies have demonstrated the potential of anaerobic digestion in converting organic waste into biogas and digestate, which can be used as organic fertilizer (Zhang et al., 2012). In parallel, research on the use of agricultural residues such as corn cobs in livestock feed has also been explored (Burroughs et al., 1945). However, these studies are generally conducted separately, focusing either on energy production or feed utilization. Limited research has systematically integrated both outputs while simultaneously evaluating the efficiency of methane production and the improvement of digestate nutritional quality within a single experimental framework. Furthermore, the linkage between technical feasibility and real-world adoption through system-based marketing approaches remains underexplored (Velenturf et al., 2021; Alqahtani & Afy-Shararah, 2025).

This study is therefore important as it addresses multiple gaps simultaneously: improving agricultural waste utilization, enhancing renewable energy production, and providing alternative feed resources for livestock systems. Such integration is particularly relevant in Indonesia, where agricultural and livestock activities are closely interconnected and resource efficiency is essential for sustainability. By converting corn cob waste into both Bio-CNG and nutrient-rich fermentation residue, this research contributes to reducing dependence on fossil fuels and commercial feed, while supporting climate change mitigation efforts (IPCC, 2019; Santolini et al., 2021).

The novelty of this research lies in three key contributions. First, it simultaneously evaluates methane production and the nutritional characteristics of fermentation residues using a controlled laboratory experimental design. Second, it compares the performance of different microbial inoculums and fermentation conditions to provide quantitative insights into process optimization. Third, it introduces a circular system marketing approach that integrates energy, feed, and fertilizer into a single agro-based model, particularly designed for implementation in corn-producing regions such as Lombok. This integrated perspective bridges the gap between laboratory findings and scalable applications in rural development contexts. Previous studies have explored the utilization of agricultural biomass waste, such as palm oil residues, as a renewable energy source within sustainability-oriented contexts (Zulkhairi & Rizki, 2026).

By combining technical analysis with a systems approach, this study not only advances scientific understanding of corn cob utilization but also offers a practical model for sustainable agriculture and renewable energy development in Indonesia. However, these studies are generally limited to specific applications and do not yet integrate biomass conversion into a comprehensive system that simultaneously produces energy, livestock feed, and supports a circular economy approach. Addressing complex agricultural and energy challenges requires integrative and problem-oriented approaches. Previous studies have shown that STEM-based and project-based learning frameworks are effective in connecting scientific concepts with real-world applications and improving problem-solving capacity (Ramdani et al., 2021). Therefore, this study aims to fill this gap by developing an integrated agro-energy model based on corn cob utilization.

Method

This study employed two main approaches: laboratory analysis and literature review. Laboratory analysis was conducted to identify the chemical and physical characteristics of corn cobs used as biogas feedstock, including moisture content, lignocellulose composition, and biodegradability potential. These data formed the basis for evaluating the suitability of corn cobs for anaerobic digestion.

Meanwhile, the literature review focused on studies supporting the application of circular economy principles in agricultural waste management, particularly those relevant to the utilization of biogas by-products such as digestate. The literature sources included scientific journals, government reports, and publications from international organizations discussing biogas technology, renewable energy, and circular economy concepts.

The combination of these two approaches enabled a comprehensive analysis of the technical potential and sustainability of biogas production systems based on corn cobs. This methodology provides a strong foundation for understanding the interconnections between agricultural waste utilization, energy production, and the principles of the circular economy – the focus of this study.

Inoculum

Two types of inoculums were used: rumen microbes and methanogenic microbes. Rumen microbes were obtained from the rumen fluid of fistulated Friesian Holstein (FH) dairy cows at the Dairy Nutrition Field Laboratory, Faculty of Animal Science, IPB University, which were fed with concentrate and elephant grass. The methanogenic inoculum was a type of Local Microorganism (MOL) produced by Syawaluddin Jamu Bumi Foundation primarily consisting of methanogenic bacteria.

Biomethane Potential Test (BMP)

In the initial phase, a biomethane production potential was conducted using the two types of inoculums. This potential test followed the Biomethane Potential Test (BMP) procedure (Shah et al., 2018; Abbassi-Guendouz et al., 2012). The first step involved inserting 4 grams of corn cob substrate into a 100 ml serum bottle. Then, 30 ml of inoculum was added to the bottle as the biofermentor. The pH level was maintained at 6.9 by adding 30 ml of mineral buffer, along with 20 ml of distilled water, bringing the digest volume to 80 ml. All bottles were sealed anaerobically with rubber stoppers and aluminum crimps. The samples were then batch-fermented and incubated at the designated treatment temperatures: 39°C and room temperature (27°C).

Gas production was measured using the Theodore method by injecting a 10 ml syringe through the rubber stopper on days 2, 4, and 6 of incubation. The total gas volume was determined based on the amount collected in the syringe at room temperature (~27°C) and atmospheric pressure (1 atm). This volume was then converted to moles using Gay-Lussac's law (Appels et al., 2008) at 273 K and 1 atm:

$$pV = nRT \tag{1}$$

Where: p = pressure (1 atm), V = gas volume (m^3), R = universal gas constant ($8.314\ JK^{-1}.mol^{-1} = 1.99\ cal.mol^{-1}.K^{-1}$), T = temperature (K), n = number of moles.

The gas was then reacted with barium hydroxide ($Ba(OH)_2$) with an indicator, causing CO_2 to react and form barium carbonate. The amount of CO_2 formed was calculated toichiometrically based on the weight of barium carbonate. Methane volume was calculated by subtracting the CO_2 volume from the total gas volume. The normality was then converted to molarity, similarly to the total gas. Other gases such as H_2S were ignored due to their very low quantities.

Analysis of Fermentation Residue Composition (Sludge)

This analysis aimed to assess the potential of fermentation residues for reuse as animal feed. A proximate analysis was conducted to determine the moisture, ash, protein, fat, nitrogen-free extract (NFE), crude fiber, and total digestible nutrients (TDN) of the residue.

pH and Metabolite Product Analysis

Measurement of pH and volatile fatty acids (VFA) was carried out as indicators of fermentation process stability. VFA measurement was performed using the steam distillation method as a conventional analytical approach widely applied in anaerobic digestion studies (Chatterjee & Mazumder, 2018; Nativ et al., 2021).

Experimental Design

This study was conducted from January to February 2022. The experimental design used was a 3×3 factorial Completely Randomized Design (CRD), with Factor A consisting of three types of inoculums, namely:

Factor A in this study consisted of different types of inoculums, including rumen microbes incubated at 39°C, rumen microbes at room temperature, and methanogenic microbes at room temperature. These variations were designed to compare the effectiveness of microbial sources and temperature conditions in influencing the anaerobic digestion process and biogas production.

Factor B was the fermentation duration, consisting of three levels: 2, 4, and 6 days. Each treatment was replicated twice. The observed parameters included:

Substrate Degradation

$$\text{Degradation (\%)} = \frac{\text{(Final weight} - \text{Initial substrate weight)}}{\text{(Initial substrate weight)}} \times 100\% \tag{2}$$

Efficiency of gas production (total gas, methane, and CO_2):

Gas production based on the initial substrate input

$$\text{Gas production from substrate (\%)} = \frac{\text{Gas weight}}{\text{Initial substrate weight}} x\ 100\ \% \tag{3}$$

Gas production derived from degraded material:

$$\begin{array}{c}\text{Gas production from}\\ \text{the degraded material (\%)}\end{array} = \frac{\text{Gas production from substrate(\%)}}{\text{Degradation (\%)}} \times 100\% \tag{4}$$

Stability and continuity of production, assessed by pH and VFA levels. Nutritional composition of fermentation residue, to evaluate its potential as livestock feed.

Data Analysis

The data were statistically analyzed using Analysis of Variance (ANOVA), followed by orthogonal polynomial contrast tests to identify significant differences among treatments (Gomez & Gomez, 1984; Montgomery, 2017). Statistical analysis was conducted using IBM SPSS version 25 (IBM Corp, 2017). Data on pH, VFA, and residue nutrient composition were analyzed descriptively.

Result and Discussion

General Observations

The fermentation process in all treatments proceeded well and was measurable, with varying gas production rates. This was indicated by the stability of fermentation pH, volatile fatty acid (VFA) production, and detectable gas production. The total gas, methane, and CO_2 production observed in this study were within normal ranges.

Substrate Degradation

Substrate degradation reflects the progress of microbial fermentation. Analysis of variance (ANOVA) showed that the percentage of substrate degradation and fermentation residue was significantly affected by the type of microbial inoculum ($P < 0.01$), incubation duration ($P < 0.01$), and the interaction between these two factors ($P < 0.05$). Orthogonal polynomial tests on incubation time revealed a highly significant linear trend ($P < 0.01$). The table and graph showing the percentage of substrate degradation are presented in Table 1 and Figure 1.

In general, degradation increased across all treatments and was considered relatively high. The highest average degradation, in descending order, was observed in: (1) Rumen microbes at room temperature; (2) Rumen microbes at 39°C; and (3) Methanogenic microbes at room temperature. For rumen microbes (both at 39°C and room temperature), degradation showed a marked increase on day 6, indicating the presence of a lag phase—a delayed onset of fermentation activity during the early stages.

Table 1. Percentage of Degradation and Fermentation Residue (%)

Product	Microbe	Temperature (°C)	Fermentation Time (days)			Average
			2	4	6	
						%
Degradation	Rumen microbes	39	38.22±4.00	38.55±0.77	41.30±0.14	39.36±2.07
	Rumen microbes	Room temperature	43.32±0.03	43.49±0.01	55.34±0.07	47.38±0.03
	Methanogen microbes	Room temperature	32.97±0.89	37.18±0.22	43.02±2.30	37.73±1.06
Residue	Rumen microbes	39	61.79±4.00	61.45±0.77	58.70±0.14	60.64±2.07
	Rumen microbes	Room temperature	56.68±0.03	56.51±0.01	44.66±0.07	52.62±0.03
	Methanogen microbes	Room temperature	67.03±0.89	62.82±0.22	56.98±2.30	62.28±1.06

In contrast, degradation using methanogenic microbes increased linearly and consistently up to day 6. These results indicate that corn cobs are degradable through a biofermentation system, although the degree and rate of degradation vary. Factors influencing degradation include substrate fiber content (cellulose, hemicellulose, and lignin), temperature, pH, microbial inoculum type, and fermentation duration (Deressa et al., 2015; Velusamy et al., 2020).

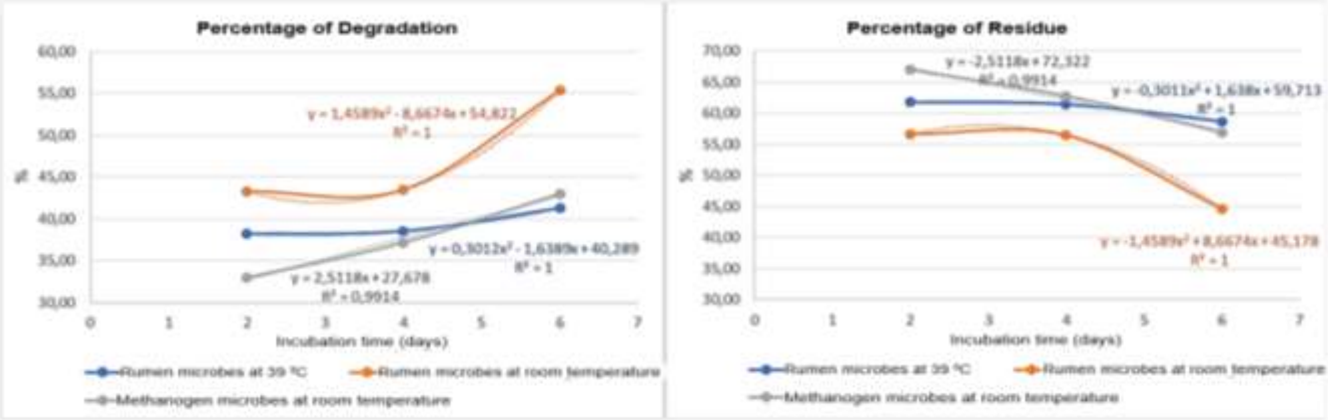

Figure 1. Graph of substrate degradation percentage (%)

Other studies using substrates with lower fiber content, different inoculum types, and longer fermentation periods than those used in corn cob biofermentation have achieved higher degradation levels. For example: (1) Bio fermentation of fruit and vegetable waste using cow dung digesters over 16 days yielded degradation rates between 63–98% (Edwiges et al., 2018); (2) Bio fermentation of tofu wastewater over 14 days resulted in a degradation rate of 56.9% based on total solids (Nisrina & Andarani, 2018); and (3) Another study using cow dung digesters reported a degradation range between 29–93% (Triolo et al., 2011).

Efficiency of Corn Cob Transformation into CO_2 and Methane (CH_4) Gas

The production of total gas, CO_2, and methane is a critical indicator for evaluating the potential of a biogas substrate to yield high-quality biogas (Li et al., 2011; Mata-Alvarez et al., 2014). The quality of biogas is determined by its methane content, as methane has a high calorific value and can be used as a fuel. Anaerobic fermentation typically produces methane, CO_2, H_2O, H_2S, NH_3, and other gases in very small proportions. The higher the methane content, the greater the energy value of the biogas, and vice versa (Yudiartono et al., 2020).

In general, the gas—particularly methane—produced in each treatment in this study falls within the range commonly reported in other studies. For instance, biofermentation using cow manure in a 2-liter fermenter produced 62.25–84.01 ml of gas with methane content ranging from 23.3–24.16% of the total gas volume (Widyasmara et al., 2012). Another study using sugarcane bagasse and cow dung over 30 days produced 29.42–114.73 liters of biogas from an initial 20-liter volume, with methane content between 23.38–27.5% (Saputra et al., 2012).

Based on the analysis of variance (ANOVA), the bioconversion of corn cob biomass into total gas, CO_2, and methane (CH_4) was significantly affected by the type of microbial inoculum ($P < 0.01$), incubation time ($P < 0.01$), and the interaction between these two factors ($P < 0.01$), as shown in Table 2. The orthogonal polynomial test for the incubation time variable revealed a highly significant linear effect ($P < 0.01$). The graph illustrating the bioconversion of corn cobs into gas is presented in Figure 2.

Table 2. Transformation of Total Gas, CO_2, and CH_4 from Corn Cob Biomass (%)

Product	Microbe	Temperature (°C)	Fermentation time (days)		
			2	4	6
Total gas	Rumen microbes	39	5.80±0.15	9.92±0.32	10.29±0.18
	Rumen microbes	Room temperature	1.38±0.18	5.51±0.04	6.47±0.19
	Methanogen microbes	Room temperature	0.46±0.03	4.95±0.22	9.11±0.08
CO_2	Rumen microbes	39	4.26±0.23	6.86±0.26	6.47±0.28
	Rumen microbes	Room temperature	1.09±0.15	4.90±0.25	5.26±0.14
	Methanogen microbes	Room temperature	0.46±0.03	0.93±0.34	5.60±0.12
CH_4	Rumen microbes	39	1.54±0.08	3.06±0.07	3.82±0.10
	Rumen microbes	Room temperature	0.29±0.02	0.61±0.29	1.20±0.05
	Methanogens	Room temperature	0.00±0.00	4.01±0.12	3.51±0.21

Based on Total Gas Production

The highest bioconversion value was obtained using rumen microbes at 39°C, followed by methanogenic microbes, and lastly, rumen microbes at room temperature. These results also correlate with the CO_2 production observed in each treatment. For rumen microbes, treatments incubated at 39°C outperformed room temperature conditions in terms of both total gas and methane production. Under room temperature conditions, bioconversion by methanogenic microbes surpassed that of rumen microbes. According to Zou et al. (2020), temperature plays a crucial role in microbial growth and the rate of biochemical reactions during biogas formation. The low gas production observed in the room temperature rumen microbial treatment may be due to the failure to reach the optimal temperature range for rumen microbial activity, which is between 36.7°C and 39.87°C (AlZahal et al., 2008).

Fermentation Rate and Gas Production, the total gas production rate varied across treatments. Gas production by methanogenic microbes increased linearly up to day 6. In contrast, gas production by rumen microbes at both 39°C and room temperature followed a quadratic trend, reaching their peak on day 5 at 10.59% and 6.53% respectively, before declining before day 6. In terms of methane gas, which is the key indicator of biogas quality, methane production by methanogenic microbes increased rapidly and significantly in a quadratic pattern. However, after day 4, methane production declined sharply. This trend did not align with the linear increase in both substrate degradation and total gas production by methanogenic microbes.

On the other hand, methane production from rumen microbes at 39°C showed a quadratic increase, peaking on day 7 at 3.92%, while methane production from rumen microbes at room temperature increased linearly. These results are consistent with the trends observed in substrate degradation and total gas production. Several factors can influence the bioconversion of substrate into biogas, including substrate nutrient composition or C/N ratio, pH, incubation temperature, buffering system, type of microbial inoculum used, and fermentation duration (Kurniati et al., 2021; Nurhilal et al., 2020; Kurniati et al., 2021; Nasir et al., 2012).

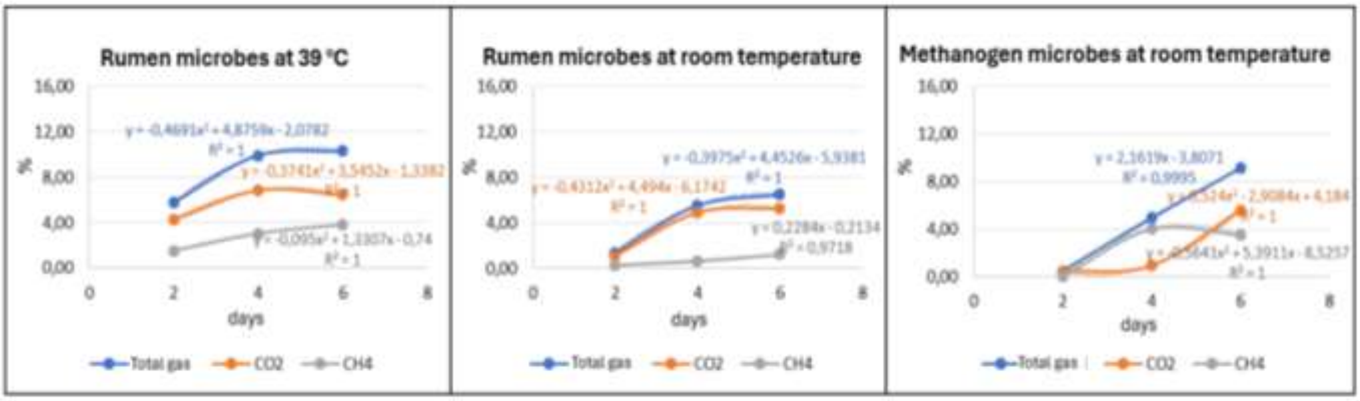

Figure 2. Transformation of total gas, CO_2, and CH_4 from corn cob biomass (%)

Gas Transformation Efficiency from Degraded Material (%)

In general, the gas transformation efficiency from each treatment was consistent and synchronized between the substrate and degraded material. Analysis of variance showed that the composition of gases resulting from corn cob substrate degradation—including total gas, CO_2, and CH_4—was significantly affected by the type of microbial inoculum ($P < 0.01$), incubation duration ($P < 0.01$), and the interaction between these two factors ($P < 0.01$). The orthogonal polynomial test for incubation duration also showed a highly significant linear result ($P < 0.01$). Table 3 presents the efficiency of gas transformation from degraded material.

In line with the results of gas transformation from the substrate, the best gas transformation from degraded material was produced by treatments using rumen microbes at 39°C, room temperature rumen microbes, and methanogenic microbes. Both types of rumen microbe treatments were able to produce a stable quadratic increase in methane gas. However, rumen microbes at 39°C were able to produce significantly higher levels of methane gas. Although the degradation and total gas transformation capacity of methanogenic microbes increased more significantly in a linear manner compared to the other treatments, the methane produced did not follow the same increasing trend. A lag phase was observed on the 4th day, where methane levels began to decline. This is suspected to be due to issues in the methane formation process by methanogenic bacteria during anaerobic gas production.

Table 3. Gas Transformation: Total Gas, CO_2, and CH_4 from Degraded Material (%)

Product	Microbes	Temperature (°C)	Fermentation Time (days)		
			2	4	6
Total gas	Rumen microbes	39	15.17±1.98	25.73±0.32	24.91±0.52
	Rumen microbes	Room temperature	3.18±0.41	12.67±0.10	11.69±0.34
	Methanogen microbes	Room temperature	1.40±0.13	13.31±0.66	21.18±1.33
CO_2	Rumen microbes	39	11.14±1.78	17.79±0.31	15.66±0.72
	Rumen microbes	Room temperature	2.51±0.36	11.27±0.56	9.51±0.24
	Methanogen microbes	Room temperature	1.40±0.13	2.51±0.92	13.01±0.42
CH_4	Rumen microbes	39	4.03±0.20	7.94±0.01	9.26±0.20
	Rumen microbes	Room temperature	0.67±0.05	1.40±0.66	2.17±0.10
	Methanogen microbes	Room temperature	0.00±0.00	10.79±0.27	8.16±0.91

Anaerobic gas production consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Corresponding to these stages, the bacteria involved are also divided into four types: hydrolytic bacteria, acidogenic bacteria, acetogenic bacteria, and methanogenic bacteria (Zhang et al., 2012). Hydrolysis is the process of breaking down large and complex molecules, whether soluble or insoluble, into smaller and simpler molecules. The second stage, acidogenesis, is a fermentation and anaerobic oxidation process that utilizes the products of hydrolysis and produces acetic acid and unbroken-chain fatty acids. The third stage, acetogenesis, involves hydrogen-producing acetogenic bacteria that convert fatty acids and ethanol into acetate, carbon dioxide, and hydrogen. The fourth stage, methanogenesis, involves the formation of methane by methanogenic bacteria (Novita et al., 2018).

Considering the strengths and weaknesses of rumen microbes at 39°C and methanogens in terms of gas transformation rate and level, it is believed that there is potential to combine rumen microbes and methanogens to complement each other's limitations and produce superior biogas.

pH Level and VFA Production

The pH level and VFA (volatile fatty acid) production are factors that can be used as indicators of the sustainability of the fermentation system. The pH levels and VFA production for each treatment are presented in Table 4.

Table 4. pH and VFA Production from Fermentation

Microbes	Temperature (°C)	pH			VFA (mmo)
		Day2	Day4	Day6	
Rumen microbes	39	6.88	6.85	6.80	130.33±3.02
Rumen microbes	Room temperature	6.87±0.03	6.80±0.01	6.78±0.01	119.64±0.00
Metanogen microbes	Room temperature	6.51±0.01	6.63±0.03	6.63±0.04	53.41±9.06

In general, each type of microbe used in the treatments was able to maintain the pH within the normal range during fermentation up to Day 6. The pH condition is an important factor to consider as it can affect biogas production (Chen et al., 2008). According to Rahayu et al. (2015), microbes involved in anaerobic degradation require an optimal pH environment. Budiyono et al. (2013) stated that anaerobic fermentation occurs at a pH of 6–8. The optimal pH for methanogenic bacteria is around ±7, and their activity decreases below pH 6. Meanwhile, Manyi-Loh et al. (2023) reported that rumen microbes require an optimal pH of approximately 6.8.

Based on the VFA produced, the activity of rumen microbes at both 39°C and room temperature was still running optimally. The VFA levels in both treatments are considered normal according to the VFA normal range by Santolini et al. (2021), which is 70–150 mM. Thus, it can be concluded that fermentation by rumen microbes proceeded well. The VFA levels of all treatments were also relatively high compared to other studies using sugarcane bagasse and cow feces, which ranged from 27.19 to 30.73 mmol (Saputra et al., 2012).

Nutritional Composition of Fermentation Residue

A proximate analysis was conducted to determine the potential use of corn cob fermentation residue as a feed ingredient. The results of the proximate analysis of the corn cob substrate and the resulting fermentation residue are shown in Table 5.

Table 5 shows an improvement in the nutritional content of the fermentation residues across all treatments. According to Indah et al. (2020), TDN levels are positively correlated with ash, protein, and fat content. This relationship is consistent with standard feed evaluation frameworks, where TDN serves as a key indicator of energy availability in feed materials (Sauvant et al., 2004) and negatively correlated with fiber content. In this study, both fiber and nitrogen-free extract (NFE) levels generally decreased, particularly in the treatment involving rumen microbes at 39°C. The reduction in these two nutrients led to an increase in TDN, indicating improved cellulolytic digestion and enhanced digestibility. The increased digestibility, as reflected in the higher TDN level, is presumed to be a result of fermentation carried out by the microbes or the digester.

Table 5. Proximate Analysis Results of Corn Cob Substrate and Fermentation Residue (%)

Product	Microbes	Temperature (°C)	% BK	Dry Matter Composition (%)					
				Ash	Protein	Fat	NFE	Fibre	TDN*)
Fermented corn cob (Susbtrat)			77.01	5.43	4.95	0.83	55.99	32.81	53.34
Corn husk			81.61	4.95	3.51	0.64	57.84	33.06	52.77
Fermented corn cobs using a biogas system (residue)	Rumen microbes	39	92.59	6.03	7.39	1.41	53.78	31.39	55.42
	Rumen microbes	Room temperature	92.71	5.88	7.65	1.12	49.38	35.97	51.27
	Methanogen microbes	Room temperature	90.87	3.57	5.76	0.47	59.05	31.16	54.74
Elephant grass [a]			22.20	12.00	8.69	2.71	43.70	32.30	52.40

*Calculation based on Sutardi (2001)

Furthermore, the decrease in NFE and fiber resulted in an increase in protein and fat content, particularly in the treatment with microbes at 39°C. In contrast, in the treatment with methanogenic microbes, only the protein level increased, while the fat level decreased. The increase in protein may also be attributed to the addition and growth of microbes (Fatmawati et al., 2020). The decrease in fiber and the significant increase in fat content suggest that methanogenic microbes tend to be more active in breaking down fiber and fat, which in turn slows down methane formation.

This explains why methane gas transformation, both from the substrate and the degraded materials by methanogenic microbes, experienced a lag phase and declined on the fourth day. In general, it can be concluded that the fermentation process using a biogas system on corn cobs can improve the nutritional quality, making the fermented corn cob residue potentially useful as livestock feed. When compared, the nutritional value of fermented corn cobs is nearly equivalent to that of elephant grass, indicating that fermented corn cobs can serve as a forage substitute and contribute to energy supply in ration formulation.

The Role of the Corn-Cattle Agroenergy System in the Circular Economy

The diagram illustrates the application of a circular economy within an integrated agricultural and livestock system. The process begins with corn cultivation, where corn cobs considered agricultural waste are repurposed as raw material for renewable energy through fermentation or anaerobic digestion. The outputs of this process biogas energy and organic residue represent a waste-to-resource conversion, which is the core of circular economy principles (Geissdoerfer et al., 2017).

The residues from bioenergy production are reused as livestock feed and organic fertilizer, supporting a closed-loop system where waste from one process benefits another. This helps reduce the use of conventional feed and chemical fertilizers, while making cattle farming more efficient and sustainable (Zhang et al., 2012). Cattle manure produced in the livestock system is likewise not wasted but processed into organic fertilizer to be reapplied to corn fields. Thus, the entire cycle—from crops to livestock and back to crops—is maintained productively. This approach not only optimizes resource use but also naturally preserves soil fertility (Appels et al., 2008).

This model also provides added economic value for farmers and livestock producers. By integrating primary production activities (corn and cattle) with by-products (biogas, fertilizer, feed), the system creates opportunities for income diversification and reduces overall production costs. This approach enhances the resilience of farming households to market fluctuations and energy crises (Suwarto & Prihantoro, 2020).

From a sustainability perspective, this system contributes to reducing greenhouse gas emissions, minimizing waste burning and chemical fertilizer use, and improving environmental quality. No waste is truly discarded; all elements within the production chain are reintegrated into the system. This aligns with the core goals of the circular economy—avoiding resource waste and maintaining ecological balance (IPCC, 2019).

The implementation of this model also holds potential for community-scale development. With appropriate technology, this agroenergy system can be applied in rural areas as part of community-based integrated agriculture. Burg et al. (2023) noted that biogas is a renewable energy source that can be utilized both at the household and communal levels, with its residue reused as organic fertilizer to support sustainable farming.

Moreover, laboratory tests have shown that the digested corn cob residue retains levels of TDN, protein, fat, and crude fiber, making it a promising feed material. The implications of this finding are significant: if corn cob-based agroenergy can be directly applied in the livestock sector, dual benefits can be realized—energy from biogas and animal feed from the digestion residue. This reinforces the principle of layered added value in the circular economy, where waste is not merely reduced, but transformed into multiple economic and ecological benefits (see Figure 3).

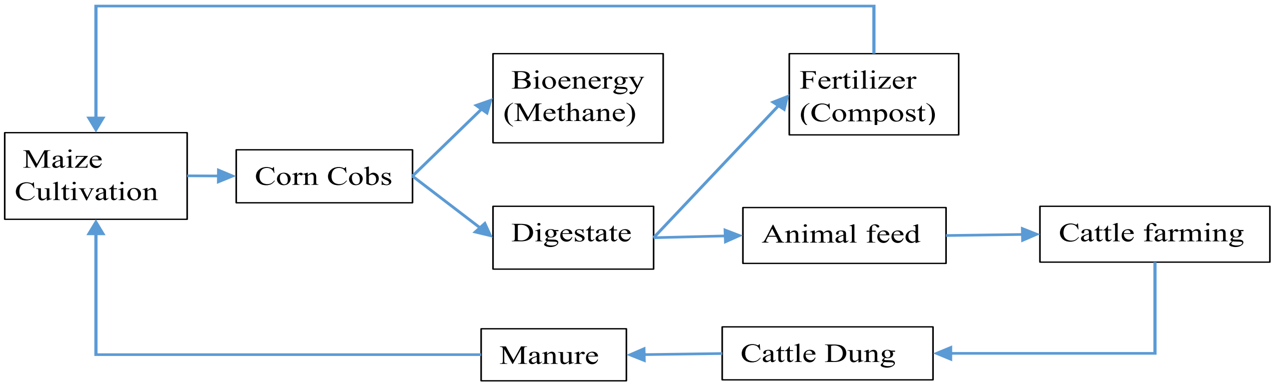

Figure 3. Circular economy model of agro-energy

Overall, the diagram not only illustrates a production flow but also reflects the philosophy of a circular economy that integrates resource efficiency, environmental sustainability, and community well-being. This model aligns with the principles of SDG 7, SDG 12, and SDG 13, and is highly relevant for the development of sustainable agriculture and energy in Indonesia.

Circular System Marketing Strategy

Although laboratory results demonstrate the high technical and nutritional potential of Bio-CNG and fermented corn cob residue products, the success of large-scale implementation heavily depends on market absorption. In the context of Eastern Indonesia, Lombok Island offers highly favorable conditions to be developed as a pilot region. Lombok Island is experiencing rising energy demand, driven by rapid development and population growth, while renewable energy utilization remains limited due to technical and economic constraints (Velenturf & Purnell, 2021). At the same time, it is one of the national centers of corn production and hosts a considerable livestock population. This combination makes Lombok a prime candidate for the development of circular-based marketing strategies.

Geographically, Lombok has an agrarian economic structure based on corn cultivation and cattle farming. Corn production in Lombok, especially in Central and East Lombok Regencies, is relatively high and generates substantial corn cob waste that has not yet been optimally utilized (Sari et al, 2024). On the other hand, smallholder cattle farming is also widespread but faces year-round limitations in the supply of high-quality forage. This situation creates a dual need for both energy and feed that can be addressed through the bioconversion of corn cobs.

The marketing strategy is directed toward the development of a territorial-based circular system, integrating corn production, corn cob waste processing, Bio-CNG and fermented feed production, as well as the reuse of residues on agricultural land. Marketing is not carried out as a single product (e.g., only Bio-CNG), but rather as a system package (Geissdoerfer et al., 2017). This package is offered as a simultaneous solution for renewable energy and food to livestock farmers, farmer cooperatives, or village-based business groups located near corn production centers and livestock areas.

Corn production centers in Lombok can serve as pilot sites for the development of community-scale Bio-CNG production units located near livestock enclosures. Mapping of corn and livestock centers is essential to determine distribution points and optimize the supply chain. Areas such as Praya Timur, Sikur, and Terara are examples of regions with spatial proximity between cornfields and cattle farms. In such locations, marketing is not only product-based but also location- and production-relationship-based.

The circular system package marketing model can be branded as an "Integrated Corn-Livestock Bioenergy S ystem," offered to village governments, BUMDes (village-owned enterprises), or farmer-livestock cooperatives. Within this package, users receive not only the products (gas, feed, organic fertilizer) but also basic processing systems (fermentation tools, technical training, waste management practices). The added value lies in efficiency and reduced dependency on external inputs (such as LPG or commercial feed), as well as long-term cost savings.

The main barrier to marketing this system is the need for a mindset shift among farmers and livestock keepers who are not yet familiar with circular approaches and fermentation technologies. Therefore, the initial strategy should focus on establishing pioneer communities through intensive training, subsidies for initial equipment, and incentives for farmer groups willing to adopt this system. A successful pilot will serve as the most effective promotional tool for market expansion in other regions.

From a policy perspective, the marketing of this system requires regional regulatory support that encourages the use of renewable energy and local feed sources. Circular system marketing aligns with the Sustainable Community Energy Independence Program supported by Pertamina, which includes forest greening efforts in Lombok (Alqahtani & Afy-Shararah, 2025). When aligned with SDG targets, the marketing can be framed as a direct contribution to SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production).

Through the circular system-based marketing approach in Lombok, Bio-CNG and fermented feed derived from corn cobs become more than just energy and feed products—they become components of a rural economic transformation that is independent, green, and sustainable. This system can be replicated in other regions with similar economic and ecological structures, strengthening Lombok's role as a national model in agricultural waste utilization for local energy and food independence.

Conclusion

This study demonstrates that rumen microbes are effective inoculants for Bio-CNG production from corn cobs, achieving stable methane yields under both room temperature and optimal 39°C conditions, with performance comparable to methanogenic microbes but with greater stability. The addition of local microorganisms (MOL) further enhances substrate degradation and improves the linearity of metabolic conversion into methane. Although methanogenic microbes showed fluctuating methane production, the combination of rumen microbes and MOL presents a synergistic potential to improve overall gas conversion efficiency. Quantitatively, the post-digestion residue of corn cobs shows improved nutritional quality, approaching elephant grass, particularly in terms of total digestible nutrients (TDN), crude protein, fat, and crude fiber content. This indicates that a single biomass input can simultaneously generate two valuable outputs: renewable energy and nutrient-enriched animal feed, directly supporting the study's objective of developing an integrated agro-energy system. The circular agro-energy model integrating corn cultivation and cattle farming proves effective in converting agricultural waste into valuable resources, reducing environmental impacts, and increasing system efficiency. This closed-loop approach aligns with sustainable agricultural principles and contributes to reduced greenhouse gas emissions while enhancing local economic value. However, this study is limited to laboratory-scale analysis, and the results may not fully represent field-scale conditions, particularly in terms of process stability, economic feasibility, and scalability. Variability in substrate composition and microbial performance under real conditions also requires further investigation. Future research should focus on pilot-scale implementation, optimization of microbial consortia (rumen microbes–MOL combinations), and comprehensive techno-economic analysis to assess feasibility at the farm or regional level. In addition, long-term studies on feed safety and animal performance using fermentation residues are needed. In conclusion, this study provides strong evidence that corn cob-based Bio-CNG production integrated with feed generation is a promising strategy for advancing renewable energy development and sustainable agricultural systems, particularly in rural Indonesia.

Acknowledgments

The authors gratefully acknowledge the financial and institutional support provided by the IREEM Foundation, Indonesia, which made this research possible. The authors also extend their sincere appreciation to the Faculty of Animal Science and the Faculty of Economics and Management, IPB University, for providing laboratory facilities, technical assistance, and academic support during the research process. Special thanks are addressed to local partners and field contributors who supported data collection, laboratory experiments, and discussions related to the implementation of the circular agro-energy system.

Author Contributions

Conceptualization, M.A., G.S.B., and S.; methodology, M.A., G.S.B., and S.; formal analysis, G.S.B., R., S.R., B.P., D.A., and H.B.S.; investigation, R., S.R., B.P., D.A., and H.B.S.; data curation, R., S.R., B.P., D.A., H.B.S., and S.; writing—original draft preparation, G.S.B., R., S.R., B.P., D.A., H.B.S., and S.; writing—review and editing, M.A.; visualization, G.S.B. and S.; supervision, M.A.; project administration, M.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

Funding

This research and the preparation of the manuscript were fully funded by the IREEM Foundation, Indonesia.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenès, J. P., Steyer, J. P., & Escudié, R. (2012). Total solids content drives high solid anaerobic digestion via mass transfer limitation. *Bioresource Technology, 111*, 55–61. https://doi.org/10.1016/j.biortech.2012.01.174

Alqahtani, M. F., & Afy-Shararah, M. (2025). Integrating circular economy practices into renewable energy in the manufacturing sector: A systematic review of the literature. *Sustainability, 17*(16), 7301. https://doi.org/10.3390/su17167301

AlZahal, O., Kebreab, E., France, J., Froetschel, M., & McBride, B. W. (2008). Ruminal temperature may aid in the detection of subacute ruminal acidosis. *Journal of Dairy Science, 91*, 202–207. https://doi.org/10.3168/jds.2007-0535

Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science, 34*(6), 755–781. https://doi.org/10.1016/j.pecs.2008.06.002

Apriyelita, A., & Marviano, F. R. (2025). Sustainable agriculture in Indonesia: A review article on strategies, challenges, and opportunities from a scientific perspective. *Jurnal Biologi Tropis, 25*(4b), 47–52. https://doi.org/10.29303/jbt.v25i4b.10386

Arisena, G. M. K., & Pradnyandari, A. A. S. D. S. (2026). Circular economy in the agricultural sector. *Indonesian Journal of Small Scale Farming, 2*(1), 34–48. https://doi.org/10.24843/ijoss.2026.v02.i01.p04

Budiyono, Khaerunnisa, G., & Rahmawati, I. (2013). Pengaruh pH dan rasio COD:N terhadap produksi biogas dengan bahan baku limbah industri alkohol (vinasse). *Eksergi, 11*(1), 1–6. Retrieved from https://www.sciencedirect.com/science/article/pii/S0960852412002258

Burg, V., Rolli, C., Schnorf, V., Scharfy, D., Anspach, V., & Bowman, G. (2023). Agricultural biogas plant as a hub to foster circular economy and bioenergy: An assessment using substance and energy flow analysis. *Resources, Conservation and Recycling, 190*. https://doi.org/10.1016/j.resconrec.2022.106770

Burroughs, W., Gerlaugh, P., Schalk, A. F., Silver, E. A., & Kunkle, L. E. (1945). The nutritive value of corn cobs in beef cattle rations. *Journal of Animal Science, 4*(4), 373–386. https://doi.org/10.2527/jas1945.44373x

Chatterjee, B., Radhakrishnan, L., & Mazumder, D. (2017). New approach for determination of volatile fatty acid in anaerobic digester sample. *Environmental Engineering Science*. https://doi.org/10.1089/ees.2017.0190

Deressa, L., Libsu, S., Chavan, R. B., Manaye, D., & Dabassa. (2015). Production of biogas from fruit and vegetable wastes mixed with different wastes. *Environment and Ecology Research, 3*(3), 65–71. https://doi.org/10.13189/eer.2015.030303

Edwiges, T., Frare, L., Mayer, B., Lins, L., Triolo, J. M., Flotats, X., & Costa, M. S. S. M. (2018). Influence of chemical composition on biochemical methane potential of fruit and vegetable waste. *Waste Management, 71*, 618–625. https://doi.org/10.1016/j.wasman.2017.05.030

Fatmawati, N., Agustono, & Lamid, M. (2020). Effect of probiotic duration and dose of coffee peel fermentation on crude protein and crude fiber. *IOP Conference Series: Earth and Environmental Science, 441*(1). https://doi.org/10.1088/1755-1315/441/1/012035

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons.

Hayati, R., Jafrizal, Armadi, Y., Kesumawati, N., & Usman. (2025). Optimization of growth and yield of several varieties of green beans (Vigna radiata L.) using solid oil palm waste on red-yellow podzolic soil in Bengkulu. *Jurnal Penelitian Pendidikan IPA, 11*(6), 42–51. https://doi.org/10.29303/jppipa.v11i6.1155

IBM Corp. (2017). *IBM SPSS Statistics for Windows, version 25.0*. IBM Corp.

Indah, A. S., Permana, I. G., & Despal. (2020). Model pendugaan total digestible nutrient (TDN) pada hijauan pakan tropis menggunakan komposisi nutrien. *Sains Peternakan, 18*(1), 38–43. http://dx.doi.org/10.20961/sainspet.v%vi%i.35684

IPCC. (2019). *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories*. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2019rf/

Kurniati, Y., Rahmat, A., Malianto, B. I., Nandayani, D., & Pratiwi, W. S. W. (2021). Review analisa kondisi optimum dalam proses pembuatan biogas. *Rekayasa, 14*(2), 272–281. https://doi.org/10.21107/rekayasa.v14i2.11305

Li, Y., Park, S. Y., & Zhu, J. (2011). Solid-state anaerobic digestion for methane production from organic waste. *Renewable and Sustainable Energy Reviews, 15*(1), 821–826. https://doi.org/10.1016/j.rser.2010.07.042

Manyi-Loh, C. E., & Lues, R. (2023). Anaerobic digestion of lignocellulosic biomass: Substrate characteristics (challenge) and innovation. *Fermentation, 9*(8), 755. https://doi.org/10.3390/fermentation9080755

Manzini, F., Islas-Samperio, J. M., & Grande-Acosta, G. K. (2024). Exploring corn cob gasification as a low-carbon technology. *Energies, 17*(10), 2256. https://doi.org/10.3390/en17102256

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M. S., Fonoll, X., Peces, M., & Astals, S. (2014). A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews*, 36, 412–427. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032114002664

Montgomery, D. C. (2017). *Design and analysis of experiments* (9th ed.). John Wiley & Sons.

Nasir, I. M., Ghazi, T. I. M., & Omar, R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Engineering in Life Sciences*, 12(3), 258–269. https://doi.org/10.1002/elsc.201100150

Nasrin, A. B., Raman, A. A. A., Loh, S. K., Sukiran, M. A., Bukhari, N. A., Aziz, A. A., Saad, M. F. M., Kamarudin, M. K. M., & Buthiyappan, A. (2020). Characteristics and techno-economic potential of bio-compressed natural gas (Bio-CNG) from palm oil mill effluent (POME). *IOP Conference Series: Materials Science and Engineering, 736*(2), 1–6. https://doi.org/10.1088/1757-899X/736/2/022060

Nisrina, H., & Andarani, P. (2018). Pemanfaatan limbah tahu skala rumah tangga menjadi biogas sebagai upaya teknologi bersih di Laboratorium Pusat Teknologi Lingkungan – BPPT. *Jurnal Presipitasi, 15*(2), 139–147. https://doi.org/10.14710/presipitasi.v15i2.139-140

Novita, E., Wahyuningsih, S., & Pradana, H. A. (2018). Variasi komposisi input proses anaerobik untuk produksi biogas pada penanganan limbah cair kopi. *Jurnal Agroteknologi, 12*(1), 43–57. https://doi.org/10.19184/j-agt.v12i1.7887

Nurhilal, M., Purwiyanto, & Aji, G. M. (2020). Pengaruh komposisi dan waktu fermentasi campuran limbah industri tahu dan kotoran sapi terhadap kandungan gas methane pada pembangkit biogas. *Jurnal Teknologi Terapan, 6*(1), 47–54. https://doi.org/10.31884/jtt.v6i1.239

Rahayu, A. S., Karsiwulan, D., Yuwono, H., Trisnawati, I., Mulyasari, S., Rahardjo, S., Hokermin, S., & Paramita, V. (2015). *Buku panduan: Konversi POME menjadi biogas: Pengembangan proyek di Indonesia*. United States Agency for International Development; Winrock International.

Ramdani, A., Jufri, A. W., & Gunawan. (2021). STEM-based project-based learning implementation to improve scientific literacy. *Jurnal Penelitian Pendidikan IPA*, 7(1), 1–10. https://doi.org/10.29303/jppipa.v7i1.552

Rahman, S. M. M. (2019). Value retention options in circular economy: Issues and opportunities. *Sustainability, 11*(17), 4723. https://doi.org/10.3390/su11174723

Santolini, E., Bovo, M., Barbaresi, A., Torreggiani, D., & Tassinari, P. (2021). Turning agricultural wastes into biomaterials: Assessing the sustainability of scenarios of circular valorization of corn cob in a life-cycle perspective. *Applied Sciences, 11*(14), 6281. https://doi.org/10.3390/app11146281

Saputra, T., Triatmojo, S., & Pertiwinigrum, A. (2012). Produksi biogas dari campuran feses sapi dan ampas tebu (bagasse) dengan rasio C/N yang berbeda. *Buletin Peternakan, 34*(2), 114–122. https://doi.org/10.21059/buletinpeternak.v34i2.97

Sari, S. A., Damanik, M., Prastowo, P., Muslim, M., Dalimunthe, M., Kabeakan, F. Y. A., & Hasibuan, H. (2024, September). Focus Group Discussion to Explore Farmers' Knowledge, Attitudes, and Skills in Utilizing Corn Cob Waste in Tambak Rejo I Village, Amplas District, Medan City. In *Proceeding International Conference of Community Service* (Vol. 2, No. 1). Retrieved from https://prosiding.umy.ac.id/iccs/index.php/iccs/article/download/259/244

Sauvant, D., Perez, J. M., & Tran, G. (2004). *Tables of composition and nutritional value of feed materials* (2nd ed.). Wageningen Academic Publishers.

Shah, T. A., & Tabassum, R. (2018). Enhancing biogas production from corn cob residue. *International Journal of Renewable Energy Research, 8*(2), 761–766. Retrieved from https://www.academia.edu/download/81484126/pdf.pdf

Suwarto, & Prihantoro, I. (2020). Studi pengembangan jagung berkelanjutan melalui integrasi dengan sapi di Tuban, Jawa Timur. *Jurnal Ilmu Pertanian Indonesia (JIPI), 25*(2), 231–238. https://doi.org/10.18343/jipi.25.2.231

Suryadi, Afdal, M., & Latief, A. (2009). Pengaruh penggantian rumput dengan pelepah sawit ditinjau dari segi kecernaan dan fermentabilitas secara in vitro gas. *Jurnal Ilmiah Ilmu-Ilmu Peternakan, 12*(1), 29–34. https://doi.org/10.22437/jiiip.v0i0.489

Sutardi, T. (2001). *Revitalisasi peternakan sapi perah melalui penggunaan ransum berbasis limbah perkebunan dan suplementasi mineral organik. Laporan akhir RUT VIII 1*. Kantor Menteri Negara Riset dan Teknologi dan LIPI

Triolo, J. M., Sommer, S. G., Møller, H. B., Weisbjerg, M. R., & Jian, X. Y. (2011). A new algorithm to characterize biodegradability of biomass during anaerobic digestion: Influence of lignin concentration on methane production potential. *Bioresource Technology, 102*, 9395–9402. https://doi.org/10.1016/j.biortech.2011.07.026

Velenturf, A. P. M., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption, 27*, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018

Velusamy, M., Weighgrebe, D., & Srinivasan, S. V. (2020). Enhancement of methane production from vegetable, fruit and flower market wastes using extrusion as pretreatment and kinetic modeling. *Water, Air, & Soil Pollution, 231*, 126. https://doi.org/10.1007/s11270-020-04469-2

Widyasmara, L., Pertiwiningrum, A., & Yusiati, L. M. (2012). Pengaruh jenis kotoran ternak sebagai substrat dengan penambahan serasah daun jati (Tectona grandis) terhadap karakteristik biogas pada proses fermentasi. *Buletin Peternakan, 36*(1), 40–47. https://doi.org/10.21059/buletinpeternak.v36i1.1275

Yudiartono, Fitriana, I., Dewi, R. E. P., Wijaya, P. T., Niode, N., & Gustriani, N. (2020). Analisa tekno-ekonomi Bio-CNG sebagai bahan bakar gas terbarukan di Indonesia. *Jurnal Energi dan Lingkungan, 14*(2), 63–74. https://doi.org/10.29122/elk.v14i2.4277

Zhang, Y., Banks, C. J., & Heaven, S. (2012). Anaerobic digestion of municipal waste. *Journal of Environmental Management, 104*, 166–174. https://doi.org/10.1016/j.jenvman.2012.03.043

Zou, H., Jiang, Q., Zhu, R., Chen, Y., Sun, T., Li, M., Zhai, J., Shi, D., Ai, H., Gu, L., & He, Q. (2020). Enhanced hydrolysis of lignocellulose in corn cob by using food waste pretreatment to improve anaerobic digestion performance. *Journal of Environmental Management, 254*, 109830. https://doi.org/10.1016/j.jenvman.2019.109830

Zulkhairi, & Rizki, D. (2026). Development of a chemistry learning model through integrated

STEM project-based learning. *Jurnal Penelitian Pendidikan IPA, 12*(3), 220–226. https://doi.org/10.29303/jppipa.v12i3.12995