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Synergistic Co-Digestion of Napier Grass, Banana Peel, and Cow Dung for Enhanced Biogas Yield

Kowrin Kishor Roy, Paban Barua Nishan, Sajal Chandra Banik*

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

This study investigates an anaerobic co-digestion strategy combining Napier grass (Pennisetum purpureum), banana peel, and cow dung to enhance biogas production. Napier grass is highly lignocellulosic (high carbon-to-nitrogen ratio) and requires additional nitrogen to optimize digestion; cow manure provides nitrogen and inoculum, while banana peels contribute readily degradable carbohydrates and moisture. Three feedstock blends were tested, with Napier:banana ratios of 1:1, 2:1, and 1:2 (by weight), each including cow dung. These mixtures were loaded into 5-L batch digesters and incubated under mesophilic conditions (28–35 °C) for ~23–24 days. During each run, biogas volume was measured daily (via water displacement) and slurry pH was maintained near neutral (≈6.8–7.5) to support methanogenesis. The co-digestion approach achieved a highest cumulative gas yield of ~2.48 L (2,481 mL) from the 1:1 Napier:banana blend, significantly outperforming other ratios. Gas composition analysis revealed relatively low hydrogen sulfide (~6–7 ppm) and a methane content of ~20–23%, indicating that the equimass feedstock combination exploited complementary biodegradation pathways while minimizing H_2S. These results highlight the novelty of the approach. By valorizing abundantly available agricultural residues, this co-digestion scheme not only delivers renewable fuel with reduced contaminants, but also advances sustainable energy generation for rural communities and improved waste management.

Keywords: Biogas, Anaerobic digestion, Napier grass, Banana peel, Cow dung, Methane yield.

1. Introduction

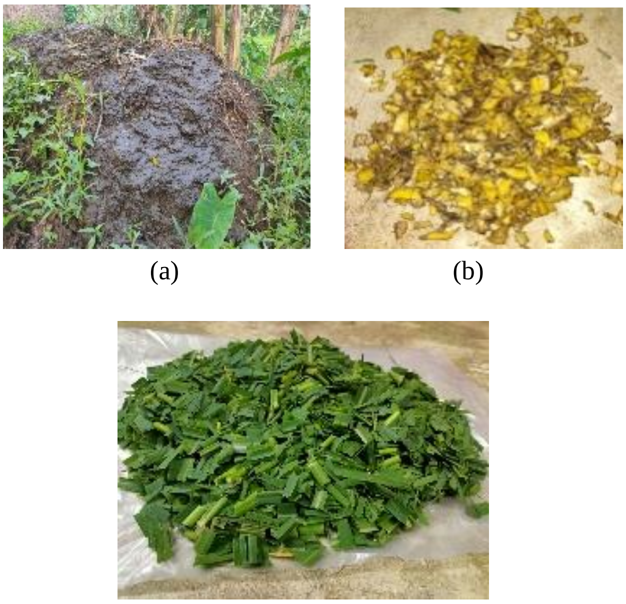
The escalating global energy demand and environmental concerns have intensified research into renewable bioenergy technologies, particularly anaerobic digestion (AD) for biogas production [1]. Napier grass (Pennisetum purpureum), characterized by high biomass productivity, short harvesting cycles, and adaptability to tropical climates, is a promising feedstock [2]. However, its elevated carbon-to-nitrogen (C/N) ratio (~41.6% C, 0.43% N) hampers microbial balance and reduces methane yield [3]. Co-digestion with nitrogen-rich substrates, such as cow dung, offers a practical strategy to optimize the C/N ratio while introducing methanogenic consortia that enhance AD performance [4]. Banana peels, a readily available agro-industrial by-product, are rich in moisture and easily degradable carbohydrates, making them an efficient co-substrate for lignocellulosic biomass [5]. Their integration into AD systems addresses waste valorization while contributing to low-cost, decentralized energy generation. AD proceeds through four biochemical stages—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—with hydrolysis often limiting lignocellulose degradation [6], [7]. Despite its early 20th-century origins, biogas technology has gained renewed interest in developing nations due to its potential to mitigate greenhouse gas emissions and reduce reliance on fossil fuels [8], [9]. The feedstocks were chosen for their local abundance and complementary properties in anaerobic digestion. Cow dung (CD) is a widely available manure that contributes microbial inoculum, moisture and alkalinity; its high protein and nitrogen content provides buffering and nutrients to the digester, offsetting high-carbon substrates. Napier grass is a high-yield C_4 forage (≈87 t ha^{-1} yr^{-1}) [10] rich in lignocellulosic carbon (cellulose /hemicellulose) with very low nitrogen. Its high C/N ratio makes hydrolysis and methanogenesis sluggish if digested alone [10]. Banana peel waste, in contrast, is abundant in fermentable sugars and moisture – "high organic content" that is readily convertible to methane, but this same high sugar load leads to rapid acidogenesis. As a result, banana-peel mono-digestion typically yields only modest methane (e.g. 77–266 L CH_4/kg VS) due to VFA accumulation and pH drop [11]. Co-digesting CD, Napier and banana peel therefore balances these effects: the cow dung supplies N and buffering capacity to neutralize the high carbon grass and the acidifying sugars of the peel, while the carbohydrate-rich peel accelerates hydrolysis of the grass fibers. In fact, prior studies report that mixing lignocellulosic grass with carbohydrate-rich wastes significantly enhances biogas output compared to mono-digestion [12]. This study investigates biogas yields from cow dung derived from cattle fed varying Napier grass–banana peel ratios, identifying a 1:1 mixture as the optimal combination for maximizing methane production.

Mishra et al. (2021) examine biogas production from biowaste via anaerobic digestion, highlighting sustainable, cost-effective approaches and advanced upgrading methods like adsorption, absorption, membranes, and cryogenic separation, along with their techno-economic and environmental value [13]. Agrahari et al. (2013) explored biogas production from kitchen waste, showing its potential to replace fossil fuels and cut greenhouse emissions. With 55–65% methane and high calorific value, efficiency improves through optimal waste-to-water ratios and solar heating [14].

This study addresses these global and local challenges by defining clear objectives: to evaluate the anaerobic co-digestion of Napier grass, banana peel, and cow dung in various proportions, and to identify optimal conditions for methane production. Specifically, we examine three Napier:banana mass ratios (1:1, 2:1, 1:2) (all mixed with fixed cow dung inoculum) under mesophilic batch digestion. The goal is to determine how substrate balance affects digestion kinetics, biogas yield, and process stability, thereby valorizing abundant agricultural residues for decentralized energy while improving waste management in rural contexts.

2. Materials And Methods

All materials were collected locally (Napier grass from the university farm, banana peels from a nearby market, cow dung from the campus barn) and cleaned of debris. The Napier grass was washed with fresh water, chopped into ~1 cm pieces, and pretreated in hot water to speed hydrolysis. Banana peels were sun-dried (30°C, 24 h) to reduce moisture, then ground to ~1 cm pieces. The cow dung was used fresh. After size reduction, feedstocks were mixed thoroughly: moisture was adjusted to ~60–80% by adding water, and cow dung was diluted into a slurry to facilitate uniform blending. A homogenous slurry of the three components was prepared, ensuring balanced nutrient distribution and microbial contact. These preparation steps (sorting, chopping, drying, and moisture adjustment) help maximize surface area and microbial accessibility, promoting efficient biodegradation.



(a) (b) (c)

Fig. 1 Feedstock selection and preparation, (a) Cow dung, (b) Banana peels, (c) Napier grass.

3. Exterimental Design

A completely randomized batch experiment was conducted over 21 days with four treatments (three co-digestion ratios and one control) and three replicates each. The treatments mixed Napier grass and banana peel in 1:1, 1:2, and 2:1 ratios (by mass), with a fixed amount of cow dung inoculum in each (Table 1). These specific ratios were selected to probe the effects of substrate balance on digestion performance. A 1:1 Napier-to-banana blend provides a moderate C/N ratio and mixed fiber/carbohydrate content, a condition often found optimal in co-digestion studies [15]. The 2:1 mixture (higher Napier content) tests a high–carbon/fiber scenario, whereas the 1:2 mixture (higher banana content) tests a low–carbon/high–readily-fermentable scenario [16]. Biochemically, Napier grass's cellulose and lignin decompose slowly [17]and demand nitrogen, while banana peel offers sugars that degrade quickly [18]. Previous work has shown Equi mass (1:1) mixtures can maximize methane yield by mitigating nutrient limitations and avoiding rapid acid buildup.

A control treatment contained cow dung only (no Napier or banana). Substrates were allocated randomly to digesters to minimize bias.

Fig. 2 Treatments mixed Napier grass and banana peel in 1:1, 1:2, and 2:1 ratios (by mass), with a fixed amount of cow dung.

Each 5-L digester was loaded with approximately 2.75–3.0 kg of material. This consisted of 1.0 kg fresh cow dung (primary inoculum and nitrogen source), 1.0 kg distilled water (to maintain ~85–90% moisture), and 1.0 ~0.75 kg of the mixed fibrous substrates (Napier + banana) depending on the treatment ratio (Table 1). Thus, the total organic loading was standardized at ~2.75–3.00 kg per digester. This loading corresponds to about 7–8% total solids, yielding a loose slurry favorable for mass transfer. The design ensured each digester had an equal inoculum mass, with only the fibrous feedstock proportions varying between treatments.

Table 1 Substrate Composition per Digester.

Component	**Mass (kg)**	**Purpose**
Cow dung	1	Primary microbial inoculum and nitrogen Source
Distilled water	1	Maintain 85–90% moisture for optimal microbial activity
Substrate mix	1.00 -0.75	Carbon source (Napier grass and banana peel, varied by treatment ratio)
Total	**2.75 -3.00**	

3.1 Digester Construction and Setup

Laboratory-scale digesters were constructed from 5-L high-density polyethylene (HDPE) bottles. Before use, each bottle was thoroughly cleaned with distilled water and dried.

Airtight seals were created by fitting the bottles with rubber stoppers pierced by gas outlet ports. Each outlet was connected via ¼″ PVC tubing to a 2-L collection bottle inverted in a water bath, so that biogas released displaced an equal volume of water (water-displacement method). After loading the substrates and water, the stopper joints were sealed with waterproof substrates and water, the stopper joints were sealed with waterproof To ensure anaerobic conditions, Add feedstock gradually to avoid sudden oxygen introduction. A soap-bubble test was performed on all connections to verify the system was gas-tight. Substrates were mixed into a homogeneous slurry before loading to distribute organic matter and inoculum evenly throughout the 4.5 L working volume. Each digester was filled to ~90% of its total volume (4.5 L) to leave sufficient headspace for biogas accumulation. The completed setup (shown schematically in Fig. 3 followed standard batch-digester protocols.

Fig. 3 Digester construction and setup.

3.2 Operating Conditions

All digesters were maintained under controlled mesophilic conditions (30–35 °C). Temperatures were monitored and kept within this range, which supports both acetoclastic and hydrogenotrophic methanogens. The initial pH of each slurry was adjusted to ~7.0 (±0.2) before incubation, as near-neutral pH prevents acid build-up that could inhibit methanogenesis. No buffering agents were added during digestion, but pH was regularly monitored.

Digesters were operated in static, batch mode for a total hydraulic retention time of twenty one days. This duration was selected to allow completion of hydrolysis, acidogenesis, and methanogenesis stages in lignocellulosic co-digestion. The 4.5 L working volume left ~10% headspace in each bottle for gas. Organic loading (2.75–3.0 kg digestate per digester) corresponded to roughly 7–8% total solids. Prior to sealing, all headspace air was displaced by N_2 purging, ensuring oxygen-free conditions throughout each run. Room temperature fluctuations (28–35 °C) were recorded but the digesters' internal temperature remained within the mesophilic band due to ambient conditions.

3.3 Analytical Methods

3.3.1 Gas volume measurement

Biogas production was measured daily by the water-displacement method. The volume of water displaced in the graduated collection cylinder directly equaled the volume of biogas produced. This method kept digester pressure constant and allowed precise quantification of cumulative biogas yield without complex instrumentation.

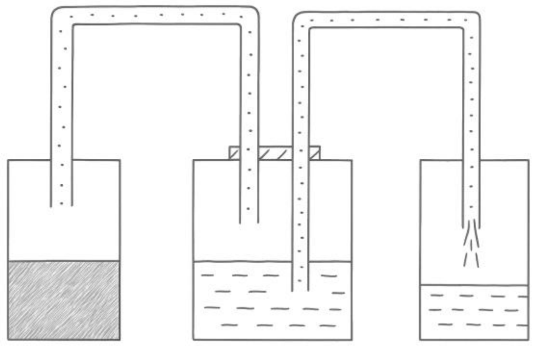


Fig. 4 Schematic setup of Water displacement method.

3.3.2 Gas composition

The methane (CH_4) and carbon dioxide (CO_2) content of the biogas was analyzed using a portable biogas gas analyzer. This instrument uses infrared and electrochemical sensors to quantify the concentration of CH_4, CO_2, H_2S, O_2, and other trace gases. Samples of gas were drawn from the headspace periodically and passed through the analyzer to determine the percent methane and carbon dioxide. These measurements allowed calculation of methane yields and gas quality from each treatment.

Fig. 5 Gas analyzer reading showing concentrations of CH_4, CO_2, and H_2S during the experiment.

3.3.3 pH monitoring

Slurry pH was measured at startup and at regular intervals using a calibrated pH meter. Maintaining near-neutral pH is critical for methanogenesis, with optimal performance typically in the 6.8–7.5 range. Data loggers recorded temperature and pH, while visual checks ensured there were no signs of digester failure (e.g. foaming or scum formation).

4. Results and Discussion

The co-digestion experiments were carried out in three separate 5 L batch digesters over a 23-day retention period. The treatments consisted of Napier grass and banana peel in 1:1 (Observation 1), 2:1 (Observation 2), and 1:2 (Observation 3) ratios, with cow dung serving as the inoculum and nitrogen source in all cases.

The batch experiments produced a typical three-phase biogas profile (lag, exponential, plateau) across all treatments. Initially, during the lag phase (days 1–3), gas output remained low as microbial communities adjusted to the new substrate environment.

Fig. 6 pH monitoring using calibrated pH meter.

This was followed by the exponential phase (days 4–17), where microbial activity intensified, leading to a sharp rise in daily gas yields, with peak production occurring in the middle of this stage. In the final stabilisation phase (days 18–23), gas generation gradually decreased, mainly due to the depletion of easily digestible organic matter, indicating the system's transition towards completion of the digestion process. Observation 1 (Napier:Banana 1:1) gave the highest total biogas (2481 mL), Observation 2 (2:1) was intermediate (2045 mL), and Observation 3 (1:2) the lowest (1615 mL). This trend – balanced Napier/peel yielding most – aligns with prior findings that a 1:1 ratio maximizes biogas yield [19].

In table 2 summarizes the total gas yield and composition for each treatment. The superior performance of the 1:1 ratio can be attributed to a more balanced C/N ratio and nutrient availability, enabling higher microbial activity and more efficient substrate utilization.

Table 2 Biogas composition across three observations.

Obs.	Napier: Banana	Total Gas (mL)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)
1	1:1	2481	23.29	31.71	16.31	6
2	2:1	2045	21.63	29.07	17.01	6
3	1:2	1615	20.25	29.12	13.92	7

Gas composition analysis revealed methane concentrations ranging from 20.25% to 23.29% and carbon dioxide levels around 29–32%. Although these methane values are lower than the 55–70% typically reported for mature anaerobic digestion systems, the consistently low hydrogen sulfide content (6–7 ppm) is a notable advantage for downstream gas utilization, as it minimizes the need for desulphurization. The elevated oxygen levels detected (13.92–17.01%) suggest the possibility of minor air intrusion, which may have contributed to the reduced methane percentage by inhibiting methanogenic activity.

In Figure 7, representing the 1:1 Napier grass–banana peel mixture (Observation 1), cumulative gas production began to increase after Day 3, with a sharp upward trend between Days 10 and 17. The production curve approached a plateau toward the end of the trial, reaching a total volume of 2481 mL. The extended mid-phase growth period suggests a well-balanced nutrient composition, enabling sustained microbial activity. The prolonged gas-release phase in the 1:1 run indicates that microbes continuously accessed degradable material over many days. This behavior aligns with co-digestion kinetics: the carbohydrate-rich fraction from banana peel is consumed early, while the fibrous Napier component is hydrolyzed more slowly, maintaining gas output. Balanced mixtures often exhibit steady biogas curves, as hydrolysis and acidogenesis proceed in tandem without rapid acid spikes or nutrient exhaustion.

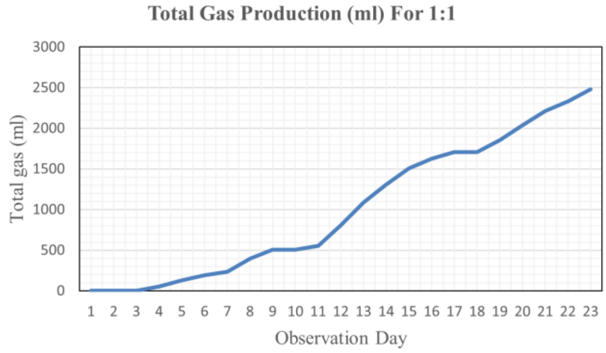


Fig. 7 Total gas production (ml) vs Day for 1:1 Napier grass-banana peel.

In Figure 8, corresponds to the 2:1 Napier grass–banana peel mixture (Observation 2). The cumulative gas curve followed a similar shape but achieved a lower final volume of 2045 mL. The rise in production during the mid-phase was less steep compared to Observation 1, indicating that the higher fibre fraction slowed hydrolysis and limited the speed of methane formation. Such sluggish gas accumulation in the 2:1 treatment is expected for lignocellulosic substrates. Napier grass's high cellulose and lignin make it recalcitrant; hydrolysis is rate-limiting. In contrast to sugar-rich waste, the breakdown of plant fibers requires more time and microbial enzyme activity. This extended lag reduces the biogas production rate, as observed in other studies where high–carbon feedstocks produce slower, delayed methane peaks.

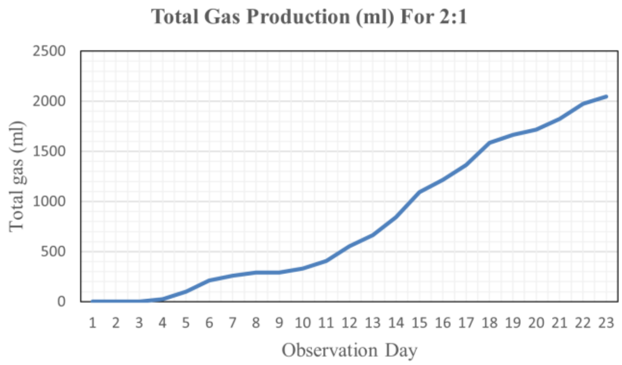


Fig. 8 Total gas production (ml) vs Day for 2:1 Napier grass-banana peel.

Figure 9 shows the results for the 1:2 Napier grass–banana peel mixture (Observation 3). Gas production increased modestly after the lag phase, but the curve began to level off earlier than in the other treatments, resulting in the lowest total yield of 1615 mL. This early plateau suggests that the easily degradable fraction from banana peel was consumed quickly, leaving insufficient material for prolonged biogas generation. The early plateau in the 1:2 curve reflects rapid digestion of the sugar-rich banana fraction. Easily degradable carbohydrates ferment quickly into volatile fatty acids, generating an initial gas surge but exhausting substrate sooner. This pattern is common in high–sugar co-digestions: methanogenesis peaks early and then tapers off once readily biodegradable organics are depleted. Consequently, methane production slows as the system becomes less buffered by new substrate, explaining the relatively low final yield for the 1:2 blend.

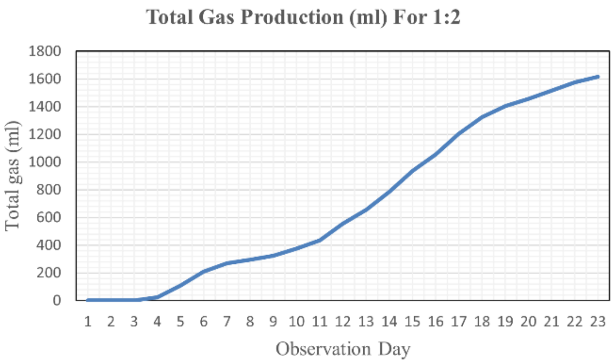


Fig. 9 Total gas production (ml) vs Day for 1:2 Napier grass-banana peel.

The three figures clearly indicate that the balanced 1:1 mixture achieved both the highest total volume and the most sustained production rate, while ratios skewed toward either high-fiber or high-sugar content reduced overall performance.

Across all treatments, the observed gas-generation patterns match known anaerobic digestion kinetics: balanced mixes sustain steady biogas output, fiber-rich mixes delay it, and sugar-rich mixes front-load it [20], [21]. These dynamics underscore the importance of substrate degradability and nutrient balance in designing efficient co-digestion systems.

5. Conclusion

This study evaluated the batch co-digestion of Napier grass and banana peel with cow dung under mesophilic conditions, comparing three substrate ratios. Across ~23 days of operation, the 1:1 Napier-to-banana blend achieved the highest cumulative gas production (~2.48 L), outperforming the 2:1 (~2.05 L) and 1:2 (~1.62 L) blends. Although total gas yield was maximized at the 1:1 ratio, measured methane content was relatively low (20–23%) and oxygen levels were unexpectedly high (14–17%), suggesting incomplete anaerobiosis or system leakage. These factors likely constrained methanogenic activity despite adequate pH and temperature ranges.

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The findings confirm that co-digestion of these locally available feedstocks can enhance volumetric biogas output; however, improvements in digester sealing, gas collection integrity, and possible pretreatment of lignocellulosic substrates are required to increase methane fraction and overall energy potential. Future investigations should incorporate continuous gas monitoring, optimized loading rates, and extended retention times to further enhance process stability and bioenergy yield.

As methanogenic microbes cannot survive in the presence of oxygen, future work should ensure fully gas-tight reactor operation (improving sealing and leak prevention) to maintain strict anaerobic conditions and maximize methane content. Rigorous pretreatment of the lignocellulosic substrates (e.g. thermal or enzymatic hydrolysis) should be evaluated to enhance hydrolysis and boost methane yield. Finally, implementing continuous (or semi-continuous) digestion with optimized feeding rates and hydraulic retention times could further stabilize the process and improve overall biogas quality.

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