



Research Article

Optimizing Biogas Production from Cow Manure: A Comparative Study of Thermal Steam Explosion and Continuous Thermal Pretreatments

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ABSTRACT

The increasing environmental challenges of cow manure disposal, alongside the rising demand for renewable energy, underscore the need for efficient waste-to-energy conversion. Cow manure, rich in organic material, holds significant potential for biogas production. However, its anaerobic digestion efficiency is often hindered by the recalcitrant nature of lignocellulosic materials. This study directly compares the effectiveness of Thermal Steam Explosion Pretreatment (TSEP) and Continuous Thermal Pretreatment (CTP) in enhancing biogas yield from cow manure. A one-factor experimental design was employed, varying temperatures between 30 °C and 50 °C using Design Expert 7.0 software. Biogas volume was measured via the water displacement method, and gas composition was analyzed using gas chromatography. The results indicate that TSEP, particularly at an optimal temperature range of 47 °C to 49 °C, yielded higher biogas volumes and superior methane concentrations exceeding 57%, with minimal carbon dioxide content. Numerical optimization confirmed these findings, identifying highly desirable operational conditions with a strong desirability index. Overall, TSEP proves to be a highly effective pretreatment method, significantly improving both the quantity and quality of biogas from cow manure. These findings have important implications for biogas production, suggesting that TSEP could play a crucial role in advancing sustainable waste management and renewable energy generation.

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1. INTRODUCTION

Managing cow manure (CM) poses a significant environmental challenge due to rising waste volumes and increasingly stringent disposal regulations (Baek et al., 2020). As agricultural production intensifies to meet global food demands, the increasing volume of CM has further complicated waste management and environmental sustainability (Khoshnevisan et al., 2021). Historically, CM was often discarded in landfills or applied directly to agricultural lands as fertilizer without prior treatment (Zohorovi et al., 2019). This practice, while initially convenient, has led to severe environmental consequences.

The practice of directly applying untreated CM to fields results in nutrient runoff, contributing to the eutrophication of water bodies (Gomez-Brandn et al., 2013). Eutrophication, caused by excessive nutrient loading, leads to algal blooms that deplete oxygen in aquatic environments, resulting in the death of fish and other aquatic organisms (Prasad & Prasad, 2019). Additionally, the decomposition of waste, such as CM, in landfills generates methane, a potent greenhouse gas that significantly contributes to climate change (Blair & Mataraarachchi, 2021). These environmental impacts are worsened by the potential for CM to harbor pathogens. These pathogens can contaminate water supplies, posing significant

health risks to both humans and animals (Alegbeleye et al., 2020).

These unsustainable practices have driven a shift toward more effective and environmentally friendly waste management solutions. Regulatory frameworks have become increasingly stringent, aiming to reduce the environmental footprint of agricultural waste and promote waste-to-energy technologies (Duque-Acevedo et al., 2020). Growing awareness of these challenges underscores the need for innovative approaches to CM management that minimize environmental harm while converting CM into a valuable resource for sustainable energy production.

In response to the environmental challenges posed by CM, anaerobic digestion (AD) technology has been widely adopted in countries with strict waste disposal regulations, such as Germany and Denmark (Vasco-Correa et al., 2018). AD involves the microbial decomposition of organic materials without oxygen, producing biogas primarily composed of methane and carbon dioxide. This process not only converts waste into valuable energy but also stabilizes waste, produces bio-fertilizers, and reduces greenhouse gas emissions (Salihu & Alam, 2016).

The AD of CM is an effective method for waste treatment and energy production. The CM contains 8-20% total solids with 70-85% volatile solids, including cellulose, hemicellulose,

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and lignin (Nasir et al., 2014). In addition, the process can convert 50-75% of organic matter into methane, with yields up to 620 L/kg VS added. Compared to composting, anaerobic digestion is more efficient in stabilizing CM, achieving faster degradation rates and greater conversion into gaseous end-products (Walker et al., 2009). High solid anaerobic digestion remains stable up to 15% total solids, with biomethane production rates of 352.2 mL/g VS at 10% TS and 318.6 mL/g VS at 15% TS (Abid et al., 2021). Considerably, AD becomes more cost-effective when biogas is used as a transport fuel (Murphy & Power, 2006). To enhance AD performance, strategies such as co-digestion, pretreatment, and additives have been explored (Li et al., 2021). Moreover, it was postulated that co-digestion with lignin-poor substrates improved synergy and lignocellulosic compound removal.

Furthermore, AD systems have proven effective in managing organic waste by stabilizing it into digestate, which can be used as a nutrient-rich soil amendment (Siles et al., 2021). This stabilization process mitigates the risk of odor, pathogen survival, and the leaching of nutrients into water bodies, which are common issues associated with untreated manure (Dong et al., 2022). Moreover, the biogas produced through AD can be harnessed for electricity and heat generation, offering a renewable energy source that contributes to reducing reliance on fossil fuels and minimizing greenhouse gas emissions (Torres-Sebastián et al., 2022).

Despite these advantages, the efficiency of AD is often constrained by the hydrolysis step, a crucial phase where complex lignocellulosic materials, such as those in CM, are broken down into simpler compounds that can be further metabolized by microorganisms (Shrestha et al., 2017). The hydrolysis of lignocellulosic substrates is hindered by the robust structure of lignin and the crystallinity of cellulose, which resist enzymatic and microbial degradation (Orlando & Borja, 2020; Yuan et al., 2021). This limitation affects the overall efficiency of biogas production, as incomplete hydrolysis can lead to suboptimal biogas yields and reduced process efficiency (Olatunji et al., 2021).

To address these challenges, researchers are exploring various pretreatment methods to enhance the hydrolysis step and improve the efficiency of AD. These methods aim to disrupt the lignocellulosic structure, making it more accessible to enzymes and microorganisms (Ethaib et al., 2020). Innovations in pretreatment technologies, such as thermal, chemical, and biological treatments, are being investigated to optimize biogas production from lignocellulosic waste materials (Khan et al., 2022). Even with this progress, there remains a need for further research to develop and refine pretreatment strategies that are both cost-effective and efficient for different types of organic residues.

Despite the established benefits of anaerobic digestion (AD) in managing CM, a significant research gap exists in optimizing pretreatment methods to enhance biogas production. Pretreatment is critical for improving the efficiency of AD by making lignocellulosic substrates more accessible to microbial degradation (Anacleto et al., 2024). Various pretreatment techniques, including thermal, chemical, and biological methods, have been investigated to address the challenges associated with the hydrolysis of complex organic materials (A. K. Kumar & Sharma, 2017). Thermal pretreatment, which involves exposing substrates to high temperatures, has been shown to disrupt the structural integrity of lignocellulose, thereby improving enzymatic and microbial access (Sun et al., 2021). Chemical pretreatments, such as acid or alkaline

treatments, can also effectively break down lignin and cellulose, facilitating enhanced biogas production (Naik et al., 2021).

However, the application of these pretreatment methods to CM has been less extensively studied, particularly regarding continuous thermal and thermal steam explosion pretreatments. Continuous thermal pretreatment involves maintaining substrates at elevated temperatures over an extended period, which can improve the efficiency of the hydrolysis process but requires precise control of temperature and treatment duration (P. Kumar et al., 2009). Similarly, thermal steam explosion pretreatment utilizes high-pressure steam to rapidly heat and expand the substrate, which can further enhance the breakdown of lignocellulosic materials (Asada et al., 2021). Despite their potential, there is limited information on the effectiveness of these methods, specifically for CM, especially when applied within controlled temperature ranges.

The existing literature suggests that while thermal and steam explosion pretreatments show promise, their optimization for CM requires a more detailed investigation. The pretreatment techniques can vary significantly in their impact depending on factors such as temperature, pressure, and treatment duration. Furthermore, the effectiveness of these methods can be influenced by the initial composition of the biomass, like CM, and the presence of other contaminants (Asada et al., 2021). This highlights the need for targeted research to evaluate how continuous thermal and thermal steam explosion pretreatments can be tailored to CM to maximize biogas yields and improve overall process efficiency. Addressing this research gap could lead to more effective and economically viable pretreatment strategies for CM, ultimately enhancing the sustainability of biogas production and contributing to more efficient waste management practices.

This study aims to address the knowledge gap in optimizing pretreatment methods for CM by investigating the efficacy of continuous thermal and thermal steam explosion pretreatments to enhance biogas production. The innovation lies in systematically evaluating these methods under controlled conditions, identifying the optimal temperature for maximizing biogas yield and methane content, and providing insights into how pretreatment enhances lignocellulosic hydrolysis. The study uses a temperature range of 30 °C to 50 °C, chosen based on preliminary findings that moderate temperatures can optimize the balance between effective hydrolysis and energy consumption, avoiding the energy-intensive extremes that may not be cost-effective. By employing a one-factor design approach with Design Expert 7.0 software, the research systematically evaluates how varying temperatures impact pretreatment efficiency, allowing for precise determination of optimal conditions.

The biogas volume is measured using the water displacement method, a standard and reliable technique for quantifying gas production in anaerobic digestion, while biogas composition is analyzed through gas chromatography to provide detailed insights into the concentration of methane and carbon dioxide. Overall, this work focused on optimizing the biogas yield from CM by comparing the performance of specific pretreatment-temperature combinations in biogas yield, aiming to contribute new insights to the existing body of knowledge in this field.

The findings have the potential to improve biogas production efficiency and contribute to better waste management practices.

2. EXPERIMENTAL

2.1. Experimental setup of biogas production using cow manure

Fresh cow manure (CM) was collected from the university dairy farm in Claveria, Misamis Oriental, Philippines. For each experimental run, 300 g of cow manure and 200 mL of water constituted the substrate for biogas production. In this study, the CM was pretreated using two methods: (1) Continuous Thermal Pretreatment (CTP) and (2) Thermal Steam Explosion Pretreatment (TSEP).

The CTP was conducted by immersing the digester containing the substrate in a water bath, which was heated using a hot plate to predetermined temperatures as specified by the experimental design (Figure 1). To ensure uniform heating and proper mixing of the substrate, the digester was equipped with a magnetic stirring device operating at a speed of 900–1300 rpm, providing consistent agitation throughout the pretreatment process (Cesaro et al., 2021; Zohorovi et al., 2019). In this setup, four bottles were used: the first bottle contained the substrate, the second bottle was filled with water with 2% NaOH solution (Hossain et al., 2021), and the third and fourth bottles were empty and prepared for water displacement when gas production began in the first bottle. As biogas was produced, the pressure built up in the second bottle, displacing the water into the third bottle and allowing the biogas to occupy the space previously filled with water (Jaro et al., 2021). The bottles were calibrated to quantify the biogas volume by measuring the total amount of displaced water (Boonkamnerd et al., 2014).

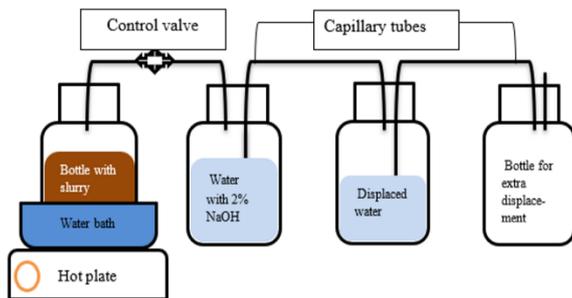


Figure 1. Experimental setup using continuous thermal treatment

For the TSEP, an additional bottle containing water was incorporated into the setup. The water in this bottle was heated using a hot plate, generating steam that was subsequently introduced into the digester to treat the substrate (Figure 2). This steam application was intended to enhance the breakdown of lignocellulosic materials, complementing the effects of the continuous thermal pretreatment. Hence, in this setup, five bottles were used: the first bottle contained the water that was heated to produce steam, the second bottle contained the substrate, the third bottle was filled with water and a 2% NaOH solution, and the fourth and fifth bottles were used for water displacement when gas production began in the second bottle. The produced biogas was determined in the calibrated bottles after water displacement.

The bottles used in the setups were 1-liter clear PET containers. To create anaerobic conditions within the system, the tops of the containers were securely sealed. The containers in the anaerobic digestion (AD) system were interconnected using a 0.2-inch capillary tube (Hossain et al., 2021). A diluted NaOH solution (2%) was introduced to minimize carbon dioxide production in the biogas, as described in a previous study (Pertiwiningrum et al., 2019). In each experimental run,

the retention time was consistently maintained at 12 days to ensure uniform conditions for the AD process. This retention period was chosen based on its relevance to mesophilic digestion systems, allowing sufficient time for the microbial community to break down the organic matter and produce biogas. All other conditions were kept consistent across all experiments to minimize variability and ensure the comparability of results.

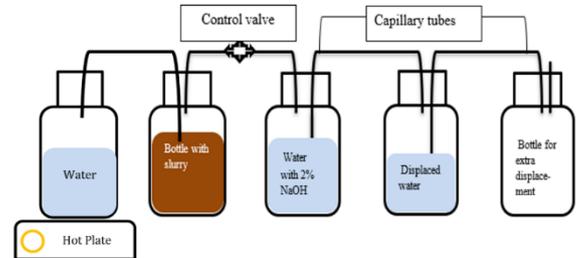


Figure 2. Experimental setup using thermal steam explosion pretreatment

2.2. Design of experiment

The experimental design was developed using the one-factor design methodology of the response surface technique, through Design Expert 7.0 software. The study focused on pretreatment methods and temperature, intending to optimize biogas production and determine the precise numerical value of temperature as the numerical operational parameter. The temperature range of 30 °C to 50 °C was carefully selected as it falls within the mesophilic range, which is widely used in anaerobic digestion due to its operational stability and practical applicability in real-world systems. This range was chosen to align with the study's goal of optimizing biogas production under conditions that are both effective and feasible for large-scale implementation.

In this study, the combination of pretreatment type and temperature is treated as a single factor with distinct levels, each representing a unique condition. This approach simplifies the experimental design and facilitates direct comparison of the performance of specific pretreatment-temperature combinations without separately analyzing their independent effects. The software generated 14 experimental runs based on the selected one-factor design (Table 1), each representing a specific combination of temperature and pretreatment conditions. These experimental runs were subsequently conducted in the laboratory to evaluate their impact on biogas yield.

Table 1. Experimental run to produce biogas using cow manure

Run	Temperature (°C)	Pretreatment
1	50	CTP
2	40	CTP
3	50	TSEP
4	35	TSEP
5	50	TSEP
6	30	CTP
7	30	TSEP
8	30	TSEP
9	45	CTP
10	50	CTP
11	40	TSEP
12	45	TSEP
13	30	CTP
14	35	CTP

CTP=Continuous Thermal Pretreatment
TSEP= Thermal Steam Explosion Pretreatment

3. METHOD

3.1. Statistical data analysis of biogas yield

The biogas yield was quantified by calculating the total volume of collected biogas. In this study, the optimization of biogas yield was a primary focus. The pretreatment methods and temperature variations in biogas production were statistically analyzed using analysis of variance (ANOVA). This analysis identified a significant combination, allowing the selection of the most appropriate model to accurately estimate biogas yield. Numerical optimization techniques were then applied within the software to generate potential solutions with high desirability, representing the unique combinations as optimal conditions for biogas production. These suggested combinations were subsequently subjected to verification runs to confirm their effectiveness and validate the model's predictive accuracy.

Gas chromatography was employed to analyze the biogas composition, determining the percentage of various gases, such as methane and carbon dioxide, within the biogas mixture (Jaro et al., 2021). The GC analysis of the biogas was performed using an Agilent 7820 A gas chromatograph equipped with fused silica capillary tubing (30 m × 0.53 mm ID × 50 µm) and a PLOT column. High-purity helium gas (99.99%), supplied by Linde Philippines, Inc., served as the carrier gas at a flow rate of approximately 15 mL/min to the GC's TCD detector. Each 15-minute run involved heating in an oven with a temperature program ranging from 30 °C to 230 °C at a ramp rate of 30 °C/min.

4. RESULTS AND DISCUSSION

4.1. Biogas yield from pretreated cow manure

In this study, two pretreatment methods were employed: Continuous Thermal Pretreatment (CTP) and Thermal Steam Explosion Pretreatment (TSEP). The experimental results presented in Table 2 demonstrate the biogas yield from cow manure subjected to various pretreatment methods and operating temperatures. The data reveal that both the type of pretreatment and the temperature influence the biogas yield, consistent with findings from recent studies and reviews on anaerobic digestion and pretreatment optimization (Wang et al., 2022; Żalys et al., 2023).

Table 2. Experimental result of biogas yield from cow manure

Run	Operating variable		Yield (mL)
	Temperature (°C)	Pretreatment	
1	50	CTP	750
2	40	CTP	975
3	50	TSEP	985
4	35	TSEP	950
5	50	TSEP	700
6	30	CTP	925
7	30	TSEP	1000
8	30	TSEP	875
9	45	CTP	825
10	50	CTP	950
11	40	TSEP	1000
12	45	TSEP	1000
13	30	CTP	850
14	35	CTP	925

Cow manure = 300 g

The results indicate that TSEP generally produced higher biogas yields compared to CTP across most temperature settings. For instance, at 30 °C, the biogas yield was 1,000 mL for TSEP (run 7) compared to 925 mL for CTP (run 6). Similarly, at 50 °C, TSEP achieved a yield of 985 mL (run 3),

whereas CTP resulted in a slightly lower yield of 950 mL (run 10). These findings suggest that TSEP is more effective in enhancing the breakdown of lignocellulosic materials, likely due to the additional mechanical disruption caused by steam explosion, which facilitates better microbial access during anaerobic digestion. This result means that TSEP has enhanced biogas production, aligning with the results of similar studies utilizing agricultural residues. Studies on rice straw (Steinbach et al., 2019), biological sludge (Pérez-Elvira et al., 2015), corn stover (Shevidi et al., 2023), and pig manure (Ferreira et al., 2014) all reported increased biogas yields compared to untreated substrates. Additionally, studies on spruce forest residues, Salix chips, and late-harvested hay demonstrated increased biogas yields after steam explosion pretreatment (Bauer et al., 2014; Horn et al., 2011; Janson et al., 2014). The pretreatment improves the enzymatic hydrolysis of polysaccharides, leading to higher and faster biogas production.

Temperature also played a crucial role in biogas yield. The highest yields for both pretreatment methods were observed at 30 °C and 40 °C. Notably, at 40 °C, both TSEP and CTP resulted in high yields, with TSEP achieving the maximum yield of 1,000 mL (run 11) and CTP reaching 975 mL (run 2). This temperature range appears to provide optimal conditions for microbial activity, which is consistent with the optimal temperature range for mesophilic anaerobic digestion (35-45 °C) reported in the literature (Kim & Lee, 2016). Interestingly, increasing the temperature to 50 °C did not consistently enhance biogas production. For example, run 5, which involved TSEP at 50 °C, yielded only 700 mL, indicating a potential inhibitory effect at higher temperatures, possibly due to thermal denaturation of microbial enzymes or an imbalance in the microbial community structure (Reedich et al., 2017). Studies have shown that hydrolysis is often the rate-limiting step in the degradation of complex substrates during anaerobic digestion, as it involves breaking down complex organic polymers into simpler molecules that can be further metabolized by microorganisms (Keating et al., 2013). Increasing the temperature generally accelerates hydrolysis by enhancing the kinetic energy of molecules, which leads to higher rates of substrate breakdown and, consequently, improved biogas production (Donoso-Bravo et al., 2009). In particular, thermal hydrolysis pretreatment is effective in enhancing the production of volatile fatty acids, which are crucial intermediates in biogas generation. This process also promotes the proliferation of hydrolytic microorganisms by creating a more favorable environment for their activity, thereby further improving the efficiency of the anaerobic digestion process (Jacquet et al., 2015). To sum up, the experimental data imply the importance of selecting appropriate pretreatment methods and operating temperatures to optimize biogas production from cow manure. TSEP, particularly at 30 °C and 40 °C, appears to likely be the most effective strategy for maximizing biogas yield in this study.

4.2. Biogas yield analysis and modeling

The analysis of variance (ANOVA) result presented in Table 3 provides critical insights into the factors influencing biogas yield from cow manure, specifically temperature and pretreatment methods. The ANOVA model itself is significant, as indicated by an F value of 4.99 and a p-value of 0.0450, suggesting that the combined effects of temperature and pretreatment significantly impact biogas production.

Looking at the results, pretreatment emerges as the more influential factor. The sum of squares for pretreatment

(7460.03) is considerably higher than that for temperature (2283.02), which is further reflected in the F value of 6.26 for pretreatment, with a corresponding p-value of 0.0409.

Table 3. Analysis of variance of biogas yield from cow manure as affected by pretreatment and temperature

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	11893.02	2	5946.51	4.99	0.0450 ^a
<i>A-Temperature</i>	2283.02	1	2283.02	1.91	0.2090 ^b
<i>B-Pretreatment</i>	7460.03	1	7460.03	6.26	0.0409 ^a
Residual	8346.98	7	1192.43		
Lack of fit	5534.48	6	922.41	0.33	0.8686 ^b
Pure error	2812.50	1	2812.50		
Cor total	20240.00	9			

^a = significant, ^b = not significant

This indicates that the type of pretreatment applied has a statistically significant effect on biogas yield at a 95% confidence level. The significance of pretreatment is consistent with recent literature emphasizing the importance of optimizing pretreatment techniques to enhance the anaerobic digestion process by improving the breakdown of lignocellulosic materials (Olatunji et al., 2021). The mechanism of pretreatment focuses on breaking down lignocellulosic materials to improve their digestibility. During pretreatment, under appropriate temperature conditions, the lignin structure is disrupted, and the bonds within cellulose and hemicellulose are weakened, increasing their accessibility to hydrolytic enzymes during anaerobic digestion (Hendriks & Zeeman, 2009). This process, known as lignocellulosic hydrolysis, enhances the availability of fermentable sugars that serve as substrates for microbial metabolism, ultimately boosting biogas production. Importantly, this mechanism does not cause lysis of the microorganisms involved in biogas production. Instead, it enhances substrate quality, making it more accessible to the microbes. The pretreatment targets the structural complexity of the lignocellulosic materials rather than the microbial cells, thereby improving microbial efficiency in converting the substrate into biogas. Maintaining the viability and activity of the microbial community is crucial, and the pretreatment methods employed were designed to support this ecosystem rather than disrupt it.

In contrast, temperature, while still a relevant factor, does not show a statistically significant effect on biogas yield in this study (p-value = 0.2090). While trends were observed at specific temperatures in the experiment, the statistical analysis found that temperature alone was not a decisive factor across the full range of conditions studied. This suggests that, within the temperature range tested (30 °C to 50 °C), the variability in biogas production may be more strongly influenced by the type of pretreatment rather than temperature alone. This temperature range lies within the mesophilic zone for anaerobic digestion, where microbial activity remains relatively stable. As a result, variations in temperature within this narrow range may not have caused significant differences in biogas yield, particularly when considering experimental variability and other factors like substrate composition or pretreatment method. This finding implies that while temperature control is essential, its impact may be secondary to the effectiveness of the pretreatment method used.

The residual sum of squares (8346.98) and the lack of fit test, with a p-value of 0.8686, indicate that the model fits the data well and there is no significant lack of fit, implying that the variability within the model's predictions is primarily due to

random error rather than systematic error. Hence, the ANOVA analysis implies the critical role of pretreatment in optimizing biogas yield from cow manure, with temperature having a less pronounced effect within the range tested. These results suggest that future efforts to enhance biogas production should focus more on refining pretreatment processes rather than solely on temperature adjustments (Karthikeyan et al., 2024).

The equations represent mathematical models for predicting the biogas volume (in mL) produced using two different pretreatment methods: CTP (Eq. 1) and TSEP (Eq. 2). These models incorporate temperature as a key variable influencing the biogas yield.

$$\text{Gas volume}_{\text{CTP}} = 848.20 + 2.075 * \text{temp } (^\circ\text{C}) \quad (1)$$

$$\text{Gas volume}_{\text{TSEP}} = 903.981 + 2.075 * \text{temp } (^\circ\text{C}) \quad (2)$$

The linear relationship between temperature and gas volume in both equations highlights the importance of temperature in the anaerobic digestion process. The positive coefficient (2.07547) associated with temperature (°C) in both equations indicates that as the temperature increases, the biogas yield increases proportionally for both pretreatment methods. This aligns with the understanding that higher temperatures typically accelerate microbial activity up to a certain level, enhancing the breakdown of organic matter and increasing biogas production (Conrad, 2023).

The equations show that TSEP consistently produces a higher baseline biogas volume compared to CTP, as indicated by the larger intercept in the TSEP equation (903.98113 mL) compared to the CTP equation (848.20755 mL). This suggests that, at any given temperature, TSEP is more effective in generating biogas than CTP. The difference in the intercepts reflects the inherent efficiency of TSEP, likely due to its more aggressive pretreatment process, which can more effectively disrupt lignocellulosic structures in cow manure, making the material more accessible to microbial degradation (Jacquet et al., 2015).

The equations function as predictive tools to estimate the biogas yield for each pretreatment method across a range of temperatures (30 °C to 50 °C). The similar temperature coefficient in both equations suggests that while temperature uniformly affects the gas production rate, the choice of pretreatment method (TSEP vs. CTP) can result in different baseline biogas volumes. For example, at 40 °C, TSEP would yield a higher biogas volume compared to CTP, emphasizing the importance of selecting the appropriate pretreatment technique based on desired outcomes.

The equal coefficients for temperature across both models suggest that the thermal sensitivity of the anaerobic digestion process is similar for both pretreatments. However, the difference in intercepts indicates that TSEP might enhance substrate availability to microbes more effectively at lower temperatures than CTP. This supports recent findings that steam explosion pretreatment can significantly improve the digestibility of lignocellulosic materials, leading to enhanced biogas production (Yu et al., 2022).

4.3. Biogas yield at optimum conditions

The data presented in Table 4 shows the results of numerical optimization for biogas yield from cow manure using the TSEP method at different temperature settings. Each solution represents a combination of temperature and pretreatment aimed at maximizing biogas production. The temperatures in these solutions range from 47.04 °C to 49.30 °C, and all

solutions utilize TSEP. The estimated biogas yield in these solutions is consistently high, ranging from 1001.61 mL to 1006.31 mL. Additionally, each solution has a desirability value of 1.0, indicating that these temperature and pretreatment combinations are optimal for achieving the maximum biogas yield within the specified range.

Table 4. Numerical optimization solutions as affected by temperature and pretreatment

Solution	Temperature (°C)	Pretreatment	Biogas yield (mL)	Desirability
1	48.75	TSEP	1005.16	1.0
2	48.97	TSEP	1005.62	1.0
3	47.04	TSEP	1001.61	1.0
4	48.66	TSEP	1004.97	1.0
5	49.30	TSEP	1006.31	1.0
Goal: temperature – in the range (30-50 °C)				
Cow manure = 300 g				

The results show that slight variations in temperature, within the narrow range of approximately 47 °C to 49 °C, do not significantly affect biogas yield, with all solutions producing over 1000 mL. The identified optimal temperatures—ranging from 47.04 °C to 49.30 °C—suggest that this is a critical range for maximizing biogas production when using TSEP. This suggests that steam explosion (TSEP) is highly effective in enhancing the breakdown of lignocellulosic material, making it more accessible to the anaerobic microorganisms responsible for biogas production. The results point to TSEP's efficiency in improving the hydrolysis of lignocellulosic materials in cow manure (CM) through a thermo-mechanochemical pretreatment process. The enhancement occurs in two stages: vapor cracking and explosive decomposition (Jacquet et al., 2015). These processes combine heat, organic acid formation, and shearing forces to modify the structural components of lignocellulosic biomass. This includes hydrolysis of hemicellulose, alteration of lignin structure, and changes in cellulose crystallinity. Steam explosion improves the material's physical properties, enhances hemicellulose hydrolysis, and facilitates lignin extraction, which ultimately aids in the hydrolysis of cellulose, increasing its suitability for biofuel production. This pretreatment method has long been considered effective for various biomass feedstocks, including agricultural residues, herbaceous crops, and hardwoods (Bułkowska & Klimiuk, 2016).

The findings from this optimization suggest that biogas production can be maximized by maintaining the digester temperature within the specified optimal range while using TSEP. For practical applications, this indicates that precise temperature control during the digestion process is crucial to achieving maximum biogas yield, especially when TSEP is employed as a pretreatment method. This insight is valuable for the design and operation of biogas plants, particularly those processing lignocellulosic materials like cow manure. However, as this study is exploratory and conducted at the laboratory scale, further research is necessary to assess energy requirements, equipment specifications, and operational costs for scaling up to an industrial level.

4.4. Biogas compositions produced at optimum conditions

The data presented in Table 5 provides an analysis of the biogas composition resulting from the anaerobic digestion of cow manure pretreated using TSEP. The gas compositions are reported as percentages of carbon dioxide (CO₂), methane (CH₄), carbon monoxide (CO), hydrogen (H₂), and nitrogen

(N₂) for two experimental runs (R₁ and R₂). The results indicate that methane (CH₄) is the predominant component of the biogas, with concentrations of 57.10% and 57.55%. This high methane content is indicative of effective anaerobic digestion, which is desirable for biogas production since methane is the primary fuel component of biogas.

Table 5. Biogas composition from pretreated cow manure via TSEP

Run	Gas composition (%)				
	CO ₂	CH ₄	CO	H ₂	N ₂ (%)
R ₁	0.06	57.10	0.00	0.00	23.79
R ₂	0.06	57.55	0.00	0.00	23.74

The nitrogen (N₂) content in the biogas mixture is relatively high, at 23.79% and 23.74%, with consistent levels across both runs, suggesting stable conditions during the digestion process. However, further optimization may be needed to reduce nitrogen levels and increase methane concentration. The carbon dioxide (CO₂) content, on the other hand, is unusually low at just 0.06% in both runs, which is atypical for biogas. This suggests that the TSEP process may effectively reduce CO₂ levels, potentially due to specific interactions with other gases or conditions during digestion. The absence of carbon monoxide (CO) and hydrogen (H₂) in both runs indicates that the anaerobic digestion process favored methane production over these less desirable gases, which are typically present in trace amounts in biogas but have lower energy content and potential toxicity. These findings align with recent studies emphasizing the benefits of steam explosion pretreatment in enhancing the digestibility of lignocellulosic materials and improving biogas quality (Abraham et al., 2020). This study demonstrated that the steam explosion pretreatment of CM using TSEP outperformed the direct heating method used in CTP. The TSEP was more effective in enhancing biogas yield and improving methane concentration, due to its ability to efficiently disrupt lignocellulosic structures. The combined effects of high-pressure steam and explosive decompression in TSEP promoted greater hydrolysis of complex organic materials, making them more accessible to microbial digestion. In contrast, CTP, relying on direct heating, lacked the mechanical and chemical impacts provided by TSEP, leading to lower biogas yields.

The biogas composition observed in this study falls within the commonly reported range of 45-75% methane for biogas produced through anaerobic digestion (Yentekakis & Goula, 2017). Similar results have been observed in biogas recovery from liquid dairy manure waste, which achieved 54% methane (Norouzi et al., 2023), and in the co-digestion of food waste with sewage sludge and poultry litter, where methane composition ranged from 55-60% (Bista et al., 2023). These results confirm the reliability and effectiveness of the digestion process employed, demonstrating its consistency with established data on biogas composition. As methane is the primary energy-contributing component of biogas, achieving a composition within this range underscores the success of the digestion process and its optimization for methane production.

5. CONCLUSIONS

This study makes a significant contribution to the understanding of biogas production, especially regarding the optimization of pretreatment methods for cow manure. The results demonstrate that Thermal Steam Explosion Pretreatment (TSEP) is considerably more effective than Continuous Thermal Pretreatment (CTP) in boosting biogas

yield and improving gas composition, particularly within the critical temperature range of 47 °C to 49 °C. TSEP consistently produced higher methane concentrations, exceeding 57%, while maintaining low carbon dioxide levels, thereby ensuring a higher energy content in the biogas. Numerical optimization techniques further supported these findings by identifying optimal conditions with a desirability index of 1.0, underscoring the robustness of TSEP as a pretreatment method. This study not only emphasizes the effectiveness of TSEP in biogas production but also lays the foundation for its potential industrial application, advancing sustainable waste-to-energy practices. It also provides valuable insights for the development of more efficient biogas production technologies. Future research could explore the optimization of additional variables, such as temperature, steam pressure, and retention time, to further maximize biogas production and enhance system efficiency.

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