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The Effects of Pretreatment with Different Concentrations of Sodium Hydroxide on Paddy Straw for Biogas Production

Tengku Roslina Tuan Yusof[1]* and Thinesh Raj A/L N Gopal[1]

[1]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02100 Arau, Perlis Indera Kayangan, Malaysia.

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ABSTRACT

Paddy straw is an abundant agricultural residue with high potential for renewable energy generation through anaerobic digestion; however, its lignocellulosic structure limits biodegradability and biogas yield. This study evaluates the effect of sodium hydroxide (NaOH) pretreatment on biogas production from fresh and dried paddy straw at concentrations ranging from 0% to 10% (w/v). The straw was immersed in NaOH solutions for 24 hours and subsequently digested under mesophilic conditions (35 °C) for 17 days in batch reactors. Biogas production was monitored daily, and cumulative yields were recorded. The results indicate that biogas production is higher in the treated sample than in to untreated sample. The treated sample shows that optimal concentrations are 6% NaOH for fresh paddy straw (65.8 mL cumulative yield) and 8% NaOH for dried paddy straw (52.05 mL). Excessive alkalinity negatively affected microbial activity and reduced performance. These findings demonstrate that optimized NaOH pretreatment improves digestibility and biogas yield, with substrate condition playing a critical role in determining optimal treatment levels, and align with SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production).

Keywords: Biogas, Pretreatment, Paddy straw, Sodium hydroxide.

1. INTRODUCTION

Paddy straw constitutes a large proportion of the residual biomass generated from rice cultivation, particularly in rice-producing countries such as Malaysia [1]. It is commonly burned in open fields or left unmanaged in agricultural areas, resulting in environmental pollution and the release of greenhouse gases. Converting paddy straw into renewable energy through anaerobic digestion offers a sustainable approach to waste management while simultaneously reducing dependence on fossil fuels [2-4].

However, the biogas potential of paddy straw is limited by its lignocellulosic composition, which consists mainly of cellulose, hemicellulose, and lignin. The presence of lignin reduces the availability of fermentable carbohydrates to microorganisms, leading to slower hydrolysis during anaerobic digestion and, consequently, lower biogas yields [5-9]. To address this limitation, various pretreatment methods have been employed to enhance biomass digestibility.

Alkaline pretreatment using sodium hydroxide (NaOH) has been reported to be effective in disrupting lignin structures, increasing fiber swelling, and improving substrate accessibility for microbial degradation. However, the effectiveness of NaOH pretreatment depends strongly on its

*Corresponding author: tengkuroslina@gmail.com

concentration, as excessive alkalinity can inhibit microbial activity and reduce digestion efficiency.

Therefore, this study aims to determine the optimal NaOH concentration to compare the performance of fresh and dried paddy straw, evaluate substrate degradation indicators, and identify an optimal pretreatment strategy that enhances biogas yield without adversely affecting microbial activity.

2. MATERIAL AND METHODS

2.1 Preparation of Paddy Straw Samples

Paddy straw was collected from Perlis, Malaysia, and prepared as fresh and dried paddy straw. Fresh paddy straw was processed immediately after collection, while dried paddy straw was air-dried to reduce moisture content prior to further use. The straw was cut into small, uniform lengths to improve handling consistency and ensure uniform exposure during pretreatment and digestion processes.

2.2 Alkaline Pretreatment Procedure

Sodium hydroxide (NaOH) was used as a chemical pretreatment agent to enhance the biodegradability of paddy straw. A series of NaOH solutions with concentrations of 0%, 2%, 4%, 6%, 8%, and 10% (w/v) were prepared using distilled water. The paddy straw samples were immersed in the respective NaOH solutions for 24 hours at ambient temperature. Upon completion of pretreatment, the samples were washed repeatedly with distilled water until the pH was neutral, thereby removing excess alkali that could inhibit microbial activity during digestion.

2.3 Anaerobic Digestion Setup and Operating Conditions

Anaerobic digestion experiments were conducted in laboratory-scale batch digesters in the form of serum bottles. The digesters were operated under mesophilic conditions at a constant temperature of 35 °C [10]. Each digester was loaded with the same working volume to maintain experimental consistency. The digestion process lasted 15 to 17 days. All experimental conditions were performed in duplicate to verify the reproducibility and reliability of the results.

Figure 1: Fermentation process in a water bath.

2.4 Biogas Monitoring and Yield Determination

Biogas production was monitored daily throughout the digestion period. The volume of biogas generated was recorded, and cumulative biogas production was calculated for each experimental condition. The biogas production trends were used to evaluate the effectiveness of NaOH pretreatment at different concentrations on the anaerobic digestion performance of both fresh and dried paddy straw.

3. RESULTS AND DISCUSSION

3.1 Influence of NaOH Pretreatment on Fresh Paddy Straw

Figures 2 and 3 show the daily and cumulative biogas production profiles of the fresh paddy straw subjected to different sodium hydroxide (NaOH) pretreatment concentrations.

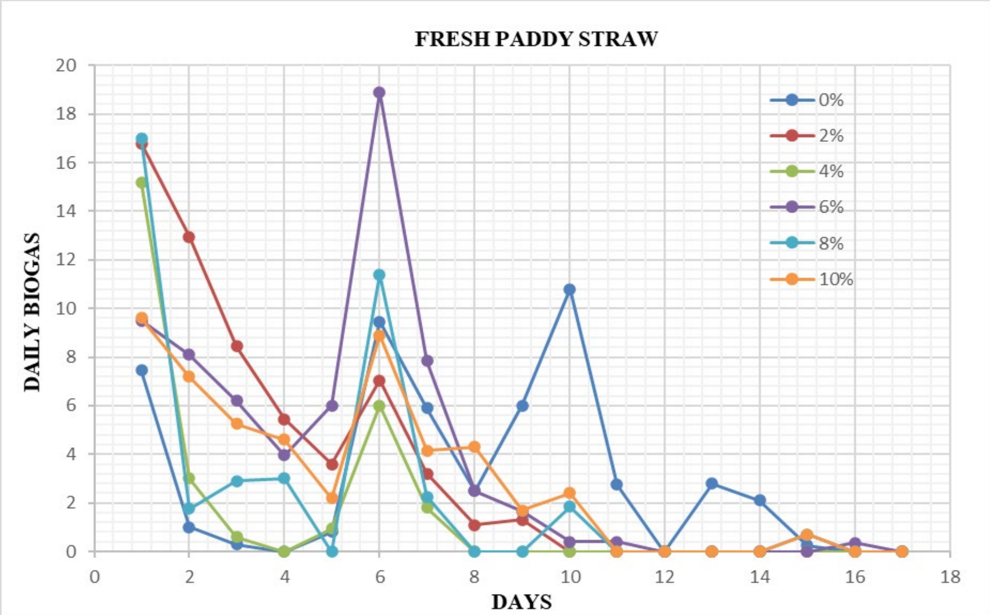

Figure 2: Daily biogas production profiles of the Fresh Paddy Straw.

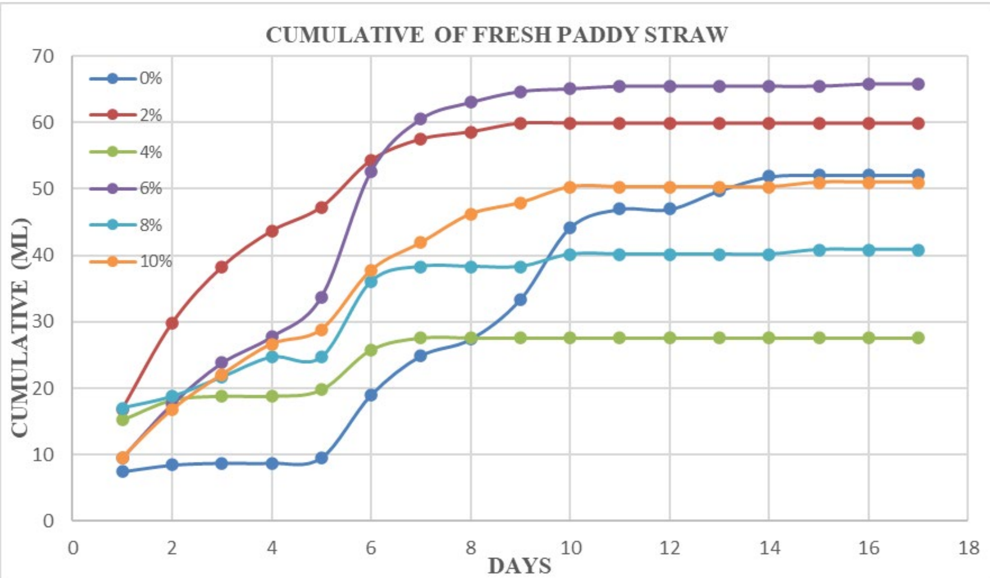

Figure 3: Cumulative biogas production profiles of the Fresh Paddy Straw.

Figure 2 illustrates the daily biogas production profiles of fresh paddy straw subjected to different NaOH pretreatment concentrations, while Figure 3 presents the corresponding cumulative biogas yields. The results show a strong dependence of biogas production on the concentration of NaOH used for pretreatment. Among the tested treatments, paddy straw pretreated with 6% NaOH exhibited the highest daily biogas production (18.9 mL) and the greatest cumulative biogas yield (approximately 65.8 mL), indicating that moderate alkaline pretreatment significantly enhances the anaerobic digestibility of fresh paddy straw. The improved biogas production at 6% NaOH enhances the accessibility of cellulose and hemicellulose to hydrolytic enzymes and methanogenic microorganisms. At this concentration, lignin disruption is sufficient to improve substrate biodegradability without inhibiting methanogenic activity. These findings are consistent with previous studies, which reported that NaOH pretreatment at moderate concentrations effectively improves biogas yield from lignocellulosic biomass such as rice straw, wheat straw, and corn stover by reducing lignin content and increasing surface area for microbial attack [11–13].

The cumulative production curves in Figure 3 exhibit typical anaerobic digestion behavior, with rapid gas accumulation during the active degradation phase followed by a plateau as the readily biodegradable fraction is depleted. The consistent superiority of the 6% NaOH treatment across both daily and cumulative trends confirms that moderate alkaline pretreatment improves conversion efficiency without inducing inhibitory effects [13-15].

Overall, Figures 2 and 3 demonstrate that optimizing NaOH concentration is critical for maximizing biogas production from fresh paddy straw. A 6% NaOH concentration provides the most favorable compromise between effective lignocellulosic disruption and preservation of microbial activity, resulting to enhanced digestion performance.

3.1 Influence of NaOH pretreatment on Dry paddy straw

The cumulative biogas production from different percentages of NaOH-pretreated (0%, 2%, 4%, 6%, 8%, 10%) dry paddy straw is shown in Figures 4 and 5, respectively.

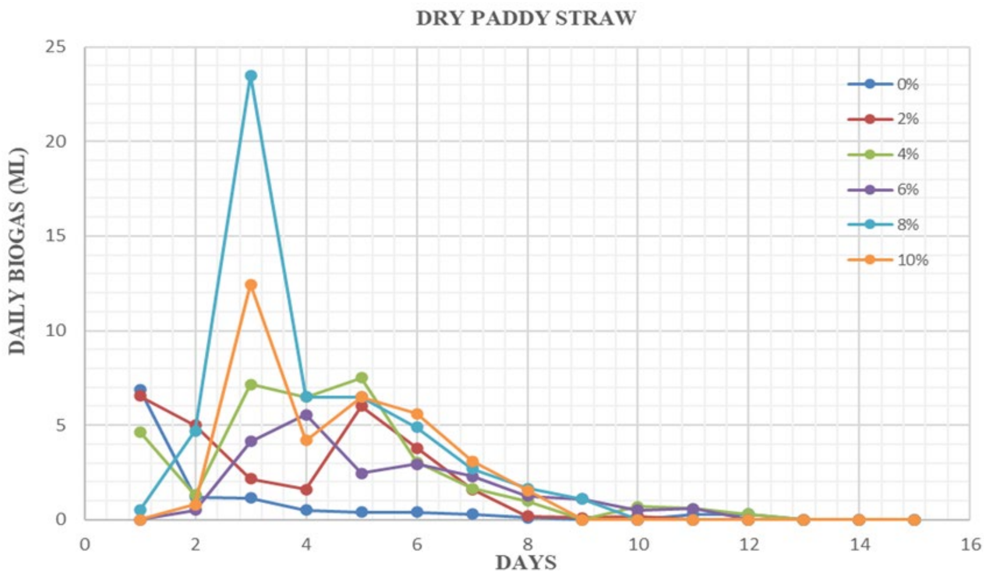

Figure 4: Daily Biogas Production of Dry Paddy Straw.

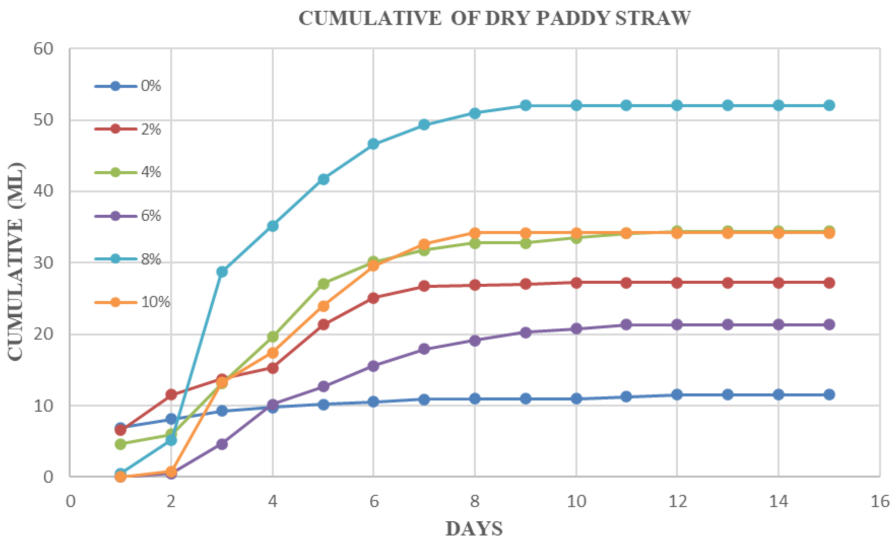

Figure 5: Cumulative Biogas Production of Dry Paddy Straw.

As shown in Figure 4, the highest daily biogas production was observed at 8% NaOH, reaching approximately 23.5 mL, whereas the lowest was observed at 6% NaOH. The enhanced daily gas generation at 8% NaOH suggests that dry paddy straw requires a stronger alkaline pretreatment to effectively disrupt its lignocellulosic matrix. Drying reduces the natural moisture content and increases structural rigidity. Therefore, higher alkali concentrations are necessary to achieve sufficient delignification and improve the accessibility of cellulose to microbial enzymes [16]. At lower pretreatment concentrations (≤6%), delignification appears inadequate, resulting in limited substrate hydrolysis and reduced methane formation. The daily biogas production pattern follows the typical anaerobic digestion trend, characterized by rapid gas generation during the active digestion phase, followed by a gradual decline as readily degradable substrates are depleted.

Figure 5 presents the corresponding cumulative biogas production profiles for dry paddy straw. The highest cumulative biogas yield (52.05 mL) was obtained at 8% NaOH pretreatment. Consistent with the daily production results, the maximum cumulative biogas output was recorded with 8% NaOH, and samples treated insufficiently (6%) produced lower total biogas volumes. The cumulative curves indicate sustained biogas production throughout the digestion period at 8% NaOH, suggesting improved substrate conversion efficiency and enhanced biodegradability resulting from more effective alkaline pretreatment. However, no further improvement was observed beyond 8% NaOH, suggesting that excessive alkalinity may begin to inhibit methanogenic microorganisms despite increased organic matter solubilization.

3.2 Effect of Pretreatment on Substrate Degradation Characteristics

Tables 1 and 2 show the degradation of substrate for fresh and dry paddy straw, respectively, on treatment with various concentrations of NaOH. For fresh paddy straw, the greatest pH decrease occurred at 6% NaOH (52.5), which also corresponded to the highest cumulative biogas yield, indicating favorable conditions for acidogenesis and methanogenesis [17]. Total solids degradation was greatest at 2% NaOH (32.02). However, positive TS changes at 10% NaOH (16.54) suggest reduced effective degradation due to alkaline inhibition [18]. Declining VS degradation from 17.26 (0%) to 4.22 (8%) further supports reduced biological utilization at higher NaOH levels.

For dry paddy straw, consistently high TS degradation (up to 40.70 at 0% NaOH) indicates stronger overall solids loss compared to fresh straw. The highest TSS degradation at 6% NaOH (51.66) reflects enhanced particulate disintegration, while significant VSS reductions (e.g., 12.79

at 0% and 9.50 at 6%) indicate improved biodegradability. These effects explain the superior cumulative biogas performance observed at 8% NaOH.

Table 1: Substrate degradation for Fresh Paddy Straw.

	NaOH concentration (%)					
Parameter	0%	2%	4%	6%	8%	10%
Moisture Content (%)	5.28	1.06	1.51	0.68	1.10	1.08
pH	25.24	4.97	51.41	52.5	50.58	45.34
Total Solids (mg/L)	16.09	32.02	25.32	0.16	2.41	16.54
Volatile Solids (mg/L)	17.25	10.20	5.06	5.16	4.21	13.52
Total Suspended Solids (mg/L)	26.15	23.29	19.54	7.94	16.17	14.21
Volatile Suspended Solids (mg/L)	0.12	0.80	0.80	0.24	0.65	1.83

Table 2: *S*ubstrate degradation for Dry Paddy Straw.

	NaOH concentration (%)					
Parameter	0%	2%	4%	6%	8%	10%
Moisture Content (%)	5.93	2.83	2.00	1.77	3.95	2.47
pH	31.02	56.41	51.84	53.75	48.91	50.31
Total Solids (mg/L)	40.70	30.36	26.51	21.86	30.23	33.43
Volatile Solids (mg/L)	1.72	0.07	0.68	1.16	2.27	2.32
Total Suspended Solids (mg/L)	19.95	13.97	41.05	51.65	9.20	25.26
Volatile Suspended Solids (mg/L)	12.79	1.74	4.52	9.49	4.86	4.90

4. CONCLUSION

This study demonstrates that sodium hydroxide pretreatment significantly enhances biogas production from paddy straw, with performance strongly dependent on alkali concentration and substrate condition. For fresh paddy straw, the optimal pretreatment was achieved with 6% NaOH, producing the highest daily biogas (18.9 mL) and cumulative yield (65.8 mL), whereas higher concentrations resulted in reduced performance due to microbial inhibition. In contrast, dry paddy straw required stronger pretreatment, with 8% NaOH yielding the highest daily (23.5 mL) and cumulative (52.05 mL) biogas production.

Substrate degradation analysis supported these trends, where moderate NaOH concentrations promoted effective lignocellulosic disruption and solids reduction, whereas excessive alkalinity limited biological activity. Overall, controlled NaOH pretreatment improves the digestibility and biogas yield of paddy straw, highlighting the importance of optimizing alkali concentration based on substrate conditions to achieve stable and efficient anaerobic digestion.

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Data Availability Statement: All data generated or analyzed during this study are included in this published article.