

A simplified biogas upgrading system for rural applications: Enhancing biomethane production through efficient carbon dioxide removal

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ABSTRACT

Biogas is increasingly recognized as a key renewable energy source for decentralized power generation, particularly in rural and agricultural communities worldwide. However, the direct use of raw biogas, typically containing high levels of carbon dioxide (CO₂), results in low heating value, reduced thermal efficiency, and operational problems such as equipment corrosion and clogging. Enhancing biogas quality through cost-effective CO₂ removal is therefore essential for maximizing energy output and improving system reliability, especially in resource-limited settings. This study proposes a simple, low-cost, and practical upgrading process suitable for decentralized biogas systems by employing adsorption and absorption techniques using readily available materials. Experiments were conducted with a fixed-bed adsorption column and a packed-column scrubber using wood chips, diatomite, activated carbon, sodium hydroxide solution, calcium carbonate, ethylamine, and water. The fixed-bed adsorption system using sodium-hydroxide-coated wood chips at a flow rate of 10–15 L/min achieved a CO₂ removal efficiency of 68%, increasing methane concentration to 79.6 (±0.9)%. The packed-column scrubber using 0.5 M NaOH demonstrated a comparable CO₂ removal efficiency of 66%, yielding upgraded biogas with 85 (±3)% methane. The NaOH solution remained effective for 50–60 minutes before reaching saturation. The resulting upgraded biogas exhibited a methane content exceeding 80% and an average heating value of 29.11 MJ/m³. Moreover, increasing NaOH concentration further enhanced CO₂ removal and methane purity. The findings highlight the potential of simple, locally sourced adsorption and absorption systems to deliver significant improvements in biogas quality, offering a viable pathway for boosting energy efficiency, extending equipment lifespan, and supporting sustainable energy development in rural and off-grid communities worldwide.

Keywords: biogas, biomethane, carbon dioxide removal, adsorption, absorption.

INTRODUCTION

Biogas, a versatile biofuel generated through the anaerobic digestion of organic matter, has emerged as a key contributor to global strategies addressing energy security, sustainable waste management, and climate change mitigation (Hadiyanto et al., 2023; Loh et al., 2017). This combustible mixture, consisting primarily of methane and carbon dioxide, can be produced from a wide range of organic feedstocks, enabling decentralized energy production in both developed and developing regions (Taghinazhad et al., 2017; Tura and Lemma, 2019). Amid growing pressure

to transition away from fossil fuels, research and development efforts into biogas and biomethane technologies have intensified worldwide (Achinas et al., 2017; Ologunde and Oladipo, 2022).

Despite the global expansion of biogas technologies, significant challenges remain in enhancing raw biogas quality prior to utilization, particularly in small-scale and community-based systems. While large-scale facilities in many countries commonly incorporate biogas upgrading technologies to meet standards for combustion efficiency, grid injection, or vehicular fuel, such technologies are often inaccessible to smaller operations due to capital costs, technical

complexity, and maintenance demands. Consequently, untreated biogas in many rural regions typically contains 45–60% methane and 35–45% carbon dioxide, along with moisture and trace contaminants such as hydrogen sulfide, nitrogen, oxygen, and siloxanes. The presence of CO₂ is especially problematic, as it directly reduces heating value, impairs combustion, and contributes to corrosion when combined with moisture to form carbonic acid, thereby shortening the lifespan of engines, piping, and other energy conversion equipment.

A wide range of CO₂ removal technologies – such as water scrubbing (Augelletti et al., 2017; Gantin et al., 2020; Olugasa and Oyesile, 2015; Wantz et al., 2023), pressure swing adsorption (Bahrun et al., 2022; Siqueira et al., 2017), amine-based chemical absorption (Kamopas et al., 2016; Meng et al., 2022), and membrane separation (Shin et al., 2019; Vrbová and Ciahotný, 2017), has been well established. However, most commercially available upgrading systems are engineered for industrial-scale or centralized biogas plants. Their high investment cost, energy requirements, and operational complexity significantly limit adoption in decentralized rural contexts, where simple, low-cost, and locally maintainable upgrading solutions are urgently needed.

Adsorption- and absorption-based CO₂ removal techniques have gained attention as promising alternatives for small- to medium-scale biogas applications due to their operational simplicity, low energy demand, and compatibility with readily available materials (Dantas et al., 2010). Fixed-bed adsorption columns using solid sorbents offer strong CO₂ selectivity, mechanical robustness, and ease of regeneration, while packed-column scrubbers using water or alkaline solutions provide efficient gas–liquid contact for CO₂ absorption under relatively mild operating conditions. Both systems are scalable, straightforward to construct, and conducive to automation, making them particularly suitable for decentralized or resource-limited biogas users (Kindi et al., 2023; Nock et al., 2014; Rainone et al., 2024).

Given the growing global demand for accessible and cost-effective biogas upgrading technologies, this study investigates two practical CO₂ removal methods; (1) absorption using a packed-column scrubber and (2) adsorption using a fixed-bed column, designed for small-scale and household-level biogas systems. The goal is to develop an efficient, low-complexity approach for enhancing

methane concentration, enabling the production of biomethane-quality fuel suitable for rural and distributed energy applications worldwide.

MATERIALS AND METHODS

Packed column scrubber

The investigation of carbon dioxide removal efficiency from biogas was carried out using a chemical absorption column system. The column was constructed from a cylindrical PVC pipe with a diameter of 10.16 cm and a length of 150 cm, as illustrated in Figure 1. The biogas inlet pipe was installed at the bottom of the column, while the outlet pipe was located at the top.

A spray nozzle was positioned at the top of the column to introduce the absorbent (chemical solution) into the system. Inside the column, a plastic media (bio-ball filter) with a surface area of no less than 1.200 m²/m³ was used to enhance the gas–liquid contact efficiency. An absorbent drain pipe was also installed at the base of the column to collect the used solution. The absorbent solution that had passed through the column was then recirculated back into the chemical storage tank for reuse.

Fixed bed adsorption column

The fixed-bed adsorption column used in this study was constructed from a cylindrical clear acrylic tube with a diameter of 10.16 cm and a length of 50 cm (Phothilangka, 2025). Both ends of the column were sealed with solid acrylic flanges of the same diameter. A 1.9 cm PVC pipe was connected to one end of the column to serve as the biogas inlet, while the opposite end functioned as the outlet for the treated biogas. Further details are illustrated in Figure 2.

Preparation of the adsorption material

The adsorbent materials used in this experiment included activated carbon, wood chips, and diatomite, all of which are readily available from local sources. Each material was prepared by cutting or selecting pieces approximately 2 × 2 × 2 cm in size, and then sieving them through a 10.67 mm mesh screen. The portion retained on the sieve was immersed in a 3.0 M ethylamine solution for 20 minutes and subsequently dried. After drying, the adsorbent material was ready for use. To enhance

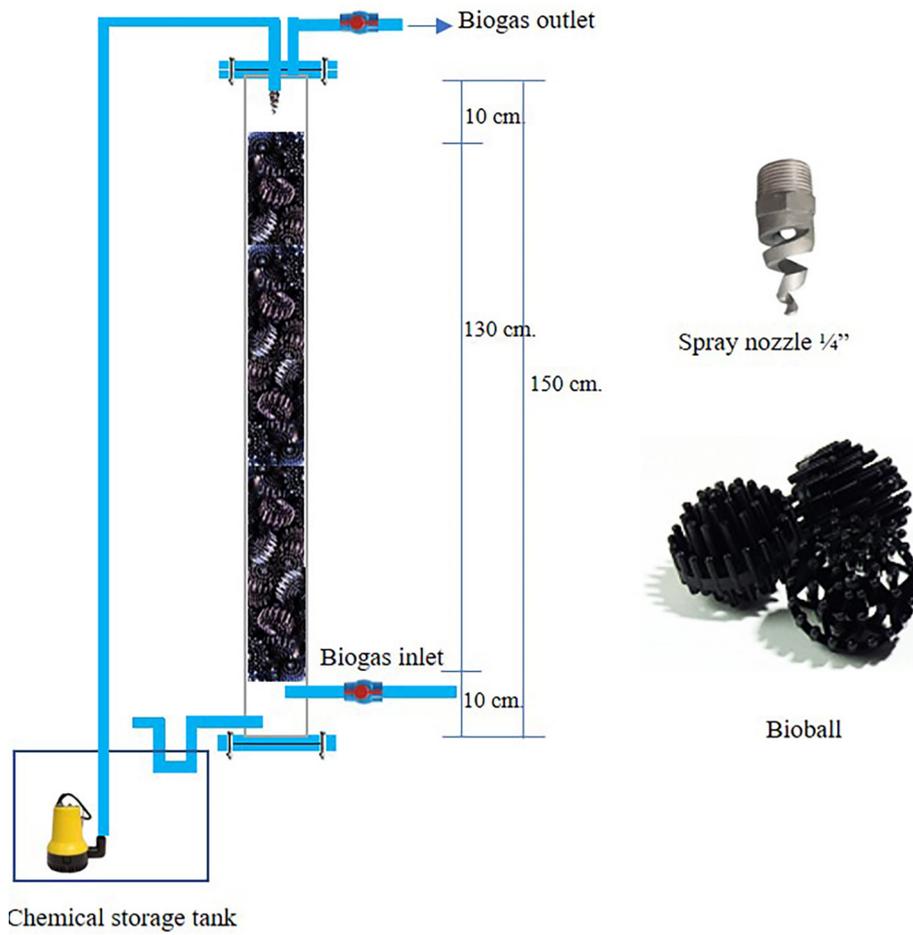


Figure 1. Packed column scrubber

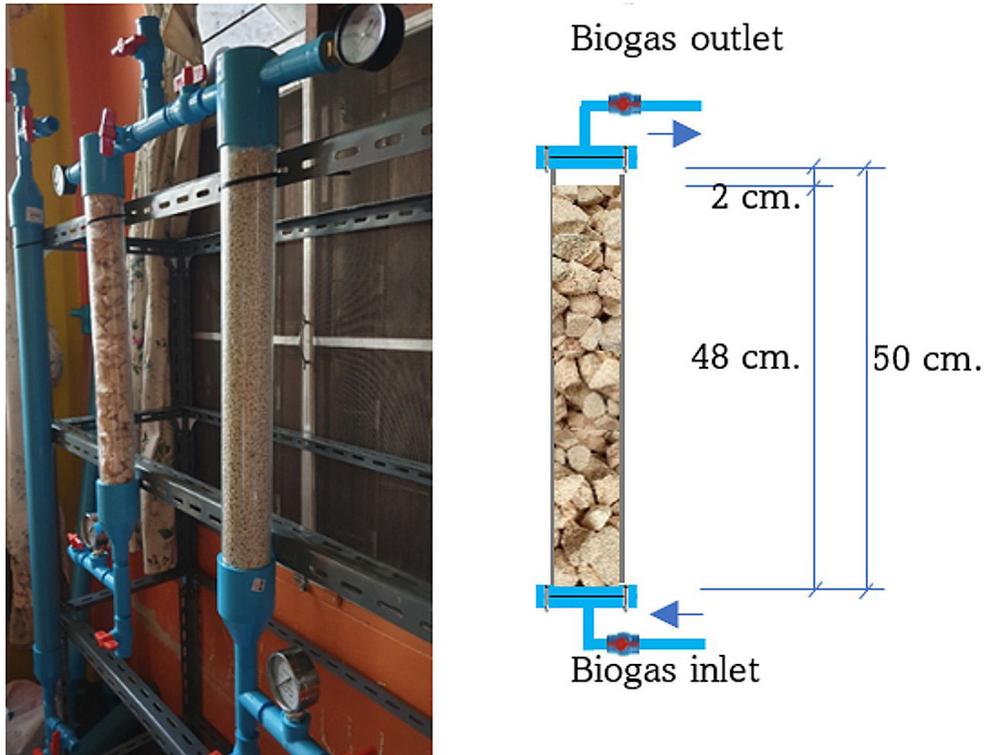


Figure 2. Fixed bed adsorption column

the adsorption properties using sodium hydroxide or calcium hydroxide (lime water), the same preparation method was applied, substituting the ethylamine solution with either a sodium hydroxide solution or a 3.0 M calcium hydroxide solution.

Materials with carbon dioxide absorption/adsorption properties in biogas

Study of materials with carbon dioxide absorption properties in biogas for packed column scrubber

The chemical solutions used for carbon dioxide absorption in biogas included 0.1 M ethylamine solution, 0.5 M sodium hydroxide solution, 3.0 M calcium hydroxide ($\text{Ca}(\text{OH})_2$), and clean water. The experiment was conducted by spraying these solutions from the top of the packed column scrubber at a flow rate of 3–3.33 L/min, counter-current to the biogas, which was introduced at the bottom of the system at a flow rate of 5 L/min.

Each absorbent solution was recirculated continuously until its absorption capacity declined or reached saturation. The composition of the biogas – namely CH_4 , H_2S , CO_2 , and O_2 – was analyzed both before entering and after exiting the experimental system. For the treated biogas, measurements were taken every 5 minutes using a portable gas analyzer (Bio Genius Model IRCD4 210406), along with parallel sample collection for laboratory analysis. The analytical results from the portable device were calibrated using a gas chromatograph (Agilent GC model 7890A).

All experiments were conducted in triplicate under a completely randomized design (CRD). Differences among treatment means were analyzed using Duncan's new multiple range test (DMRT) at a 95% confidence level ($p < 0.05$), with significance evaluated at both $p < 0.01$ and $p < 0.05$. The carbon dioxide absorption efficiency of each solution was then assessed.

Study of materials with carbon dioxide adsorption properties in biogas for fixed bed adsorption column

Each adsorbent material prepared was placed into the fixed-bed adsorption column described previously. Carbon dioxide adsorption was then investigated by allowing biogas to flow through the column under atmospheric pressure, without any pressure enhancement.

The adsorption experiments were conducted at a biogas flow rate of 5 L/min to evaluate the CO_2 adsorption capacity of each adsorbent material under standard operating conditions. The adsorption efficiency was assessed by analyzing the biogas components – namely CH_4 , H_2S , CO_2 , and O_2 – before and after passing through the adsorption column.

Measurements were taken every 5 minutes after the biogas began flowing through the column, using the same instruments and analytical methods as those employed in the packed column scrubber experiment.

RESULTS AND DISCUSSION

Carbon dioxide adsorption in biogas

Activated carbon

The results of using activated carbon for carbon dioxide adsorption indicated that biogas flowed through the column less efficiently due to the physical characteristics of activated carbon, which consists of small flakes. The typical interlayer spacing of activated carbon is approximately 0.34–0.35 nm (Ganjoo et al., 2023), resulting in limited void space between the flakes and hindering biogas flow. Therefore, in this experiment, the biogas pressure was increased to a sufficient level to ensure continuous flow through the adsorption column.

The biogas entering the adsorption column had an average carbon dioxide concentration of 32%. The experimental results showed that carbon dioxide was effectively adsorbed, reducing its concentration to an average of approximately 14%. Consequently, the methane content increased to an average of 80.35%, corresponding to a carbon dioxide removal efficiency of 56.3%.

However, after 75 minutes of operation, the carbon dioxide adsorption efficiency began to decline, as indicated by a gradual increase in the methane proportion in the treated biogas, as shown in Figure 3. This reduction in CO_2 concentration is attributed to the physical structure of activated carbon, which contains numerous small pores and microcracks that facilitate the adsorption of CO_2 molecules. Under standard conditions, modified activated carbon is capable of adsorbing between 103 and 217 mg of carbon dioxide per gram of adsorbent (Acevedo et al., 2023).

Wood chips

The study on carbon dioxide adsorption using wood chips included three types of materials: unmodified wood chips, ethylamine-coated wood chips, and sodium hydroxide-coated wood chips. Among these, the sodium hydroxide-coated wood chips demonstrated the highest efficiency in carbon dioxide adsorption, as illustrated in Figure 4.

In the adsorption experiment using biogas with an initial CO₂ concentration of 33%, the fixed-bed column system showed an efficiency of only 3% when unmodified wood chips were used. However, when the wood chips were chemically modified by coating with sodium hydroxide, the carbon dioxide adsorption efficiency significantly increased to 69.7% after approximately 12 minutes of biogas flow through the column. The final CO₂ concentration was reduced to 10%, while the methane content in the biogas increased from an average of 64% to 85%.

These findings are consistent with previous studies (Dobele et al., 2012; Serafin and Junior, 2022; Wang et al., 2024; Wu et al., 2023), which reported that the pre-treatment or chemical modification of wood-based materials can enhance their carbon dioxide adsorption performance. Naksusuk and Tangsatitkulchai (2019), reported that, in solid NaOH-impregnated materials, the primary mechanism involves surface diffusion, with surface diffusivity being approximately two orders of magnitude greater than pore diffusivity.

However, in this investigation, the carbon dioxide adsorption efficiency of sodium hydroxide-coated wood chips began to decline

after approximately 130 minutes of operation. Ethylamine-coated wood chips were found to adsorb only about 5% of the CO₂, while unmodified wood chips exhibited negligible adsorption capacity.

Diatomite

The study found that untreated diatomite has a very limited capacity to adsorb carbon dioxide. However, when its quality was enhanced by coating it with 1.0 M sodium hydroxide, its CO₂ adsorption efficiency increased significantly, with peak performance observed between the 20th and 25th minute, averaging 65%. This enhancement resulted in an increase in methane concentration from 64% to 90%.

These findings suggest that sodium hydroxide pretreatment may improve diatomite's carbon dioxide adsorption capacity by increasing surface area and promoting the formation of reactive silicate species. Nevertheless, after reaching peak efficiency, the adsorption performance declined rapidly, and the material was no longer able to adsorb carbon dioxide even though the methane concentration remained elevated at 90%.

The experimental results indicate that sodium hydroxide-coated diatomite quickly reaches saturation, as illustrated in Figure 5.

Carbon dioxide absorption in biogas

Ethylamine solution

Amine-based absorbents used in packed column systems represent a promising method for capturing carbon dioxide from biogas (Afkhampour and Mofarahi, 2017; Barzagli

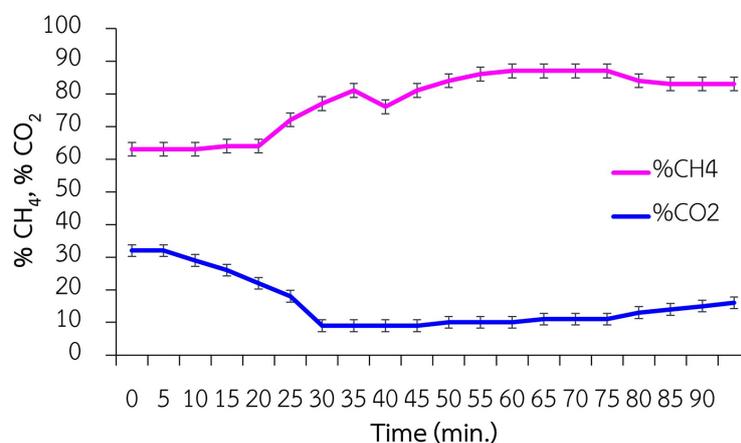


Figure 3. Carbon dioxide adsorption behavior of activated carbon

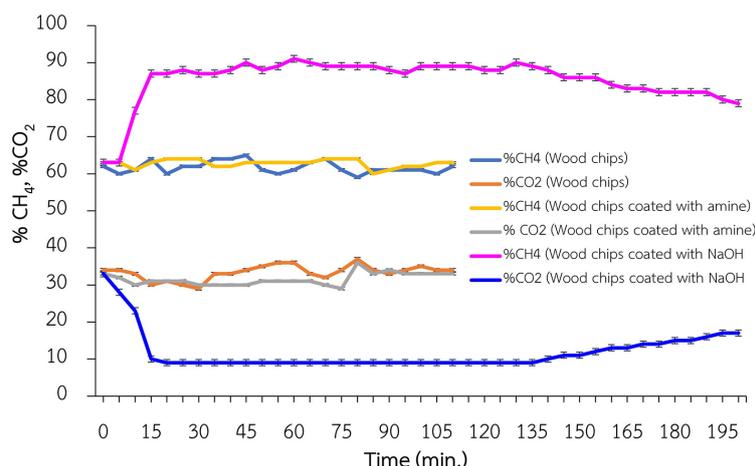


Figure 4. Carbon dioxide adsorption efficiency of wood chips with and without chemical coatings

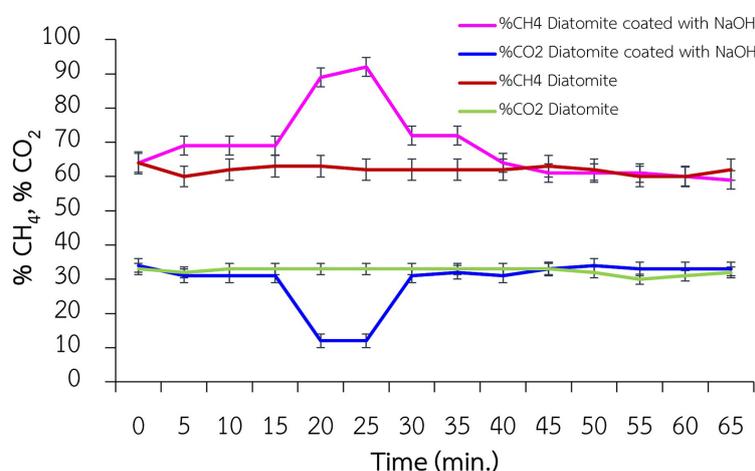


Figure 5. Carbon dioxide adsorption of diatomite and NaOH-coated diatomite

et al., 2014; Dhuyool et al., 2024; Rajiman et al., 2022). In this study, biogas was treated using a packed column scrubber with ethylamine -an amine-based solvent- at concentrations of 0.1 M and 1.0 M. The results showed that the 1.0 M ethylamine solution was more effective in capturing carbon dioxide than the 0.1 M solution.

As illustrated in Figure 6, the 1.0 M amine solution reduced the carbon dioxide concentration from 32% to 7% after 40 minutes of biogas flow through the column, achieving an average removal efficiency of 78.13%. This also resulted in an increase in methane concentration from 62% to 85%.

However, the performance of such systems is influenced by various factors, including the type of amine used, solution concentration, and the operational parameters within the packed column.

Sodium hydroxide solution

The experimental results demonstrated that a 0.5 M sodium hydroxide solution can effectively absorb carbon dioxide from biogas, reducing the CO₂ concentration from 32% to an average of only 1.95%, a reduction of more than 94%. After five minutes of biogas flow through the packed column, the methane concentration increased from 61.6% to 89.57%.

However, after approximately 80 minutes, the CO₂ concentration began to rise slightly, likely due to the sodium hydroxide solution approaching saturation, which gradually diminished its absorption capacity. This trend is illustrated in Figure 7.

Limewater

The limewater used in this experiment was prepared by dissolving calcium hydroxide

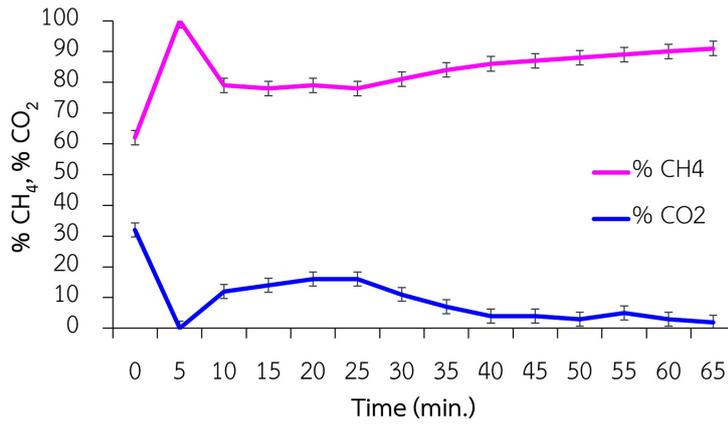


Figure 6. Carbon dioxide adsorption of 1 M ethylamine solution

(Ca(OH)₂) in water, allowing the mixture to settle, and then extracting only the clear supernatant for use in the experiment.

As shown in Figure 8, the results indicate that during the first 5–10 minutes, the proportion of carbon dioxide decreased rapidly from 34% to 12%, while the methane concentration increased from 62% to 78%. After this initial phase, the efficiency of carbon dioxide absorption gradually declined, likely due to the saturation of the lime-water solution, which reduced its ability to absorb CO₂ over extended operation.

The chemical reactions involved in the absorption process are represented in Equation 1.



Calcium carbonate

The study found that calcium carbonate (CaCO₃) was more effective at capturing carbon dioxide than limewater. It was able to reduce the CO₂ concentration in biogas from 34%

to a minimum of 10% when the biogas passed through the column for approximately 15 minutes. This process also increased the methane content from 62% to 78.9%. However, the absorption efficiency gradually declined after approximately 40 minutes of operation, as illustrated in Figure 9.

Clean water

In this experiment, tap water sourced from groundwater was used, as it is capable of absorbing a limited amount of carbon dioxide. The initial average CO₂ concentration decreased slightly from 34.2% to 33.3%, resulting in a minor increase in methane concentration from 63.0% to 64.4%, as shown in Figure 10.

One factor contributing to the relatively low absorption efficiency of water is temperature (Gul and Un, 2022), as the ambient temperature during the experiment was relatively high, averaging between 34–36 °C. However, based on the findings of this study, water was found to be significantly

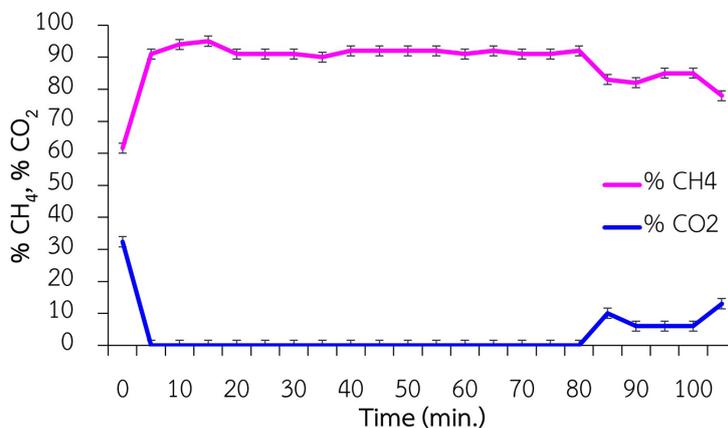


Figure 7. Carbon dioxide absorption of 0.5 M sodium hydroxide solution

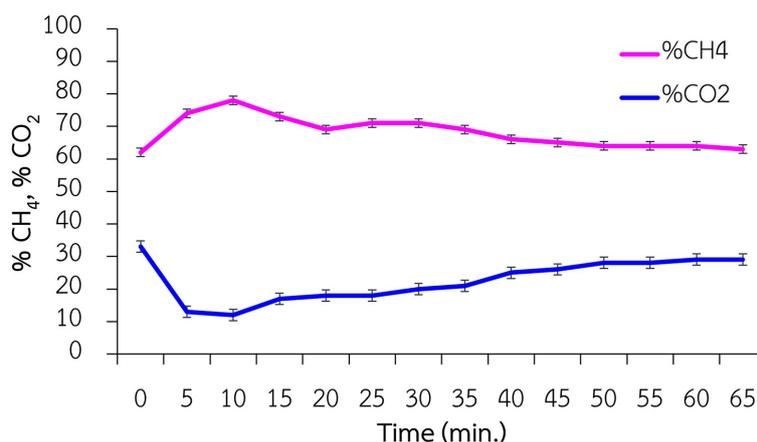


Figure 8. Absorption of carbon dioxide by limewater

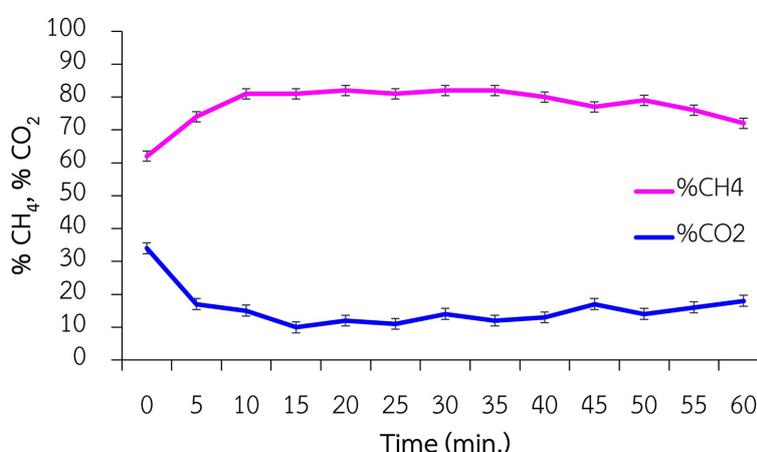


Figure 9. Absorption of carbon dioxide by calcium carbonate

less effective as a CO₂ absorbent compared to other absorbent materials tested.

Table 1 presents the carbon dioxide absorption efficiency of each absorbent/adsorbent. The results indicate that 0.5 M NaOH exhibited the highest CO₂ absorption efficiency. This finding is consistent with previous studies (Ramatsa et al., 2020; Rattanaya et al., 2021; Widyanuriawan and Sugiarto, 2014), which have reported that NaOH is highly effective in carbon dioxide removal.

Locally sourced wood chips demonstrated the second-highest performance, with an efficiency of 69.7%. As a result, wood chips were selected as the packing material and adsorbent in the fixed-bed adsorption column for subsequent experiments. To enhance their performance, the wood chips were coated with NaOH. At the same time, further CO₂ absorption experiments were conducted using the 0.5 M NaOH solution in the packed column system to remove carbon dioxide from biogas.

Development of a prototype for carbon dioxide removal and testing in a livestock farm

Fixed bed adsorption column

Carbon dioxide removal from biogas using a fixed-bed adsorption column packed with sodium hydroxide-coated wood chips as the adsorbent was investigated. The system was installed at a livestock farm and tested under full-scale operational conditions, with a biogas feed rate of 15 L/min.

The results showed that the system was able to reduce the CO₂ concentration in the biogas from an initial level of 38.5 (±0.5)% to 12.3 (±0.4)%, corresponding to an adsorption efficiency of 68%. Consequently, the methane content increased from 53.9 (±0.2)% to 79.6 (±0.9)%. The chemical reaction occurring in the column is shown in Equation (2) (Chan et al., 2025; Michelson et al., 2024; Rincón et al., 2023), which demonstrates

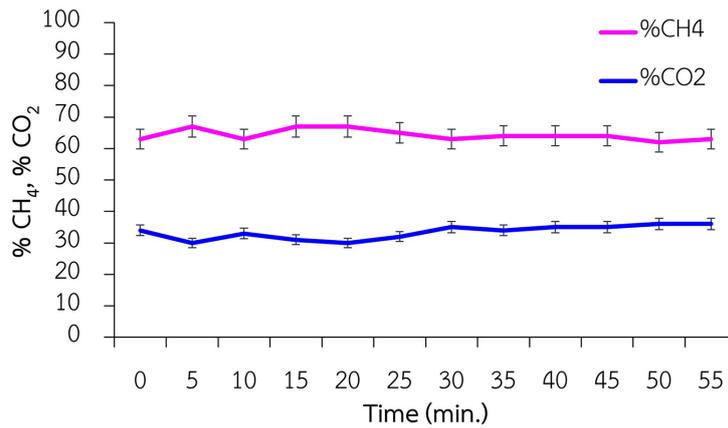


Figure 10. Absorption of carbon dioxide by clean water

Table 1. Efficiency of CO₂ removal by each adsorbent/absorbent

Materials	%CO ₂ inlet	%CO ₂ outlet	%CO ₂ removal
<i>Adsorbent</i>			
Activated carbon	32	14	56.25
Wood Chips	34	33	3
NaOH coated wood chips	33	10	69.7
Diatomite	33	30	9
NaOH coated diatomite	34	12	65
<i>Absorbent</i>			
1.0 M Ethylamine solution	32	7	78.13
0.5 M sodium hydroxide solution	32	1.95	93.91
Limewater	34	12	64.71
calcium carbonate	34	10	70.59
Clean water	34.2	33.3	2.63

that carbon dioxide reacts with sodium hydroxide to form sodium carbonate (Na₂CO₃), a water-soluble compound with alkaline properties.



This observation aligns with previous research, which indicates that the amount of CO₂ captured is limited by the available quantity of NaOH (Ghaffari et al., 2023; Yoo et al., 2013). Furthermore, the reaction efficiency is influenced by several factors (Dinul et al., 2023), as well as the CO₂ concentration in the biogas and the biogas feed rate.

Nevertheless, The CO₂ adsorption efficiency of NaOH-coated wood chips declined markedly within the first 10 minutes of operation. This rapid performance deterioration in the fixed-bed column is primarily attributed to the irreversible chemisorption mechanism of NaOH-based adsorbents. Equation 2 demonstrates that the formation of sodium

carbonate is accompanied by the consumption of hydroxide ions, which decreases the hydroxide ion concentration and adversely affects the carbon dioxide capture performance of the system.

To improve adsorbent durability and extend operational lifetime, strategies such as enhancing alkali dispersion, controlling inlet gas humidity, reducing superficial gas velocity, and optimizing bed utilization through staged or layered configurations should be considered. Alternatively, more chemically and structurally robust supports, such as activated carbon or inorganic porous materials impregnated with NaOH, may offer improved stability.

However, the experimental results indicate that CO₂ removal from biogas using wood chips coated with 3 M NaOH is not sufficiently effective for practical applications. The primary limitation lies in the short operational lifetime of the adsorbent, which becomes saturated rapidly. Consequently, the CO₂ adsorption system developed in this study

is unsuitable for improving biogas quality under continuous or long-term operating conditions.

Packed column scrubber

The results of carbon dioxide absorption using sodium hydroxide are presented in Table 2, which demonstrates that increasing the concentration of NaOH enhances absorption efficiency. This finding is consistent with previous studies on CO₂ absorption from biogas using sodium hydroxide (Dinul et al., 2023; Trisnaliani, 2020). These studies reported that a 0.25 M sodium hydroxide solution was insufficient to raise the methane content to 80%. In contrast, 0.5 M and 1.0 M sodium hydroxide solutions removed more carbon dioxide in proportion to their concentrations and were able to increase the methane content to at least 80% during a 30-minute experimental period.

Baciocchi et al. (2013) also confirmed that CO₂ removal efficiency increases with higher NaOH concentrations. In their study, using a 3.8 mol/L NaOH solution in a three-stage absorption test, they achieved a CO₂ removal efficiency of up to 90.6%, with a corresponding methane content increase of 34.2%.

However, in this full-scale investigation, when the system was operated continuously until the cumulative methane content fell below 80%, the 0.5 M NaOH solution maintained a methane content above 80% for up to 50 minutes, whereas the 1.0 M NaOH solution extended this period to approximately 75 minutes. These findings indicate that higher concentrations of sodium hydroxide are more effective in sustaining CO₂ removal and maintaining high methane content, as summarized in Table 2.

The full-scale system operation test conducted at the livestock farm yielded satisfactory results and identified suitable conditions for on-site application. Notably, the system demonstrated effective performance even with lower sodium hydroxide concentrations than those reported in previous studies. For instance, earlier research suggested that optimal conditions for CO₂ absorption from biogas in an absorber column were achieved at a flow rate of 9 L/min using a 2 M sodium hydroxide solution. The superior performance observed for CO₂ absorption using a 0.5 M NaOH solution, compared to some previous studies employing higher concentrations, can be attributed to differences in system configuration and operating conditions rather than alkali concentration alone. In the present full-scale system, enhanced

gas–liquid contact efficiency, appropriate hydraulic loading, and sufficient residence time likely facilitated effective CO₂ absorption even at lower NaOH concentrations. Moreover, operating at moderate NaOH concentrations can reduce solution viscosity and mitigate mass transfer limitations, thereby improving gas–liquid interfacial renewal and overall absorption efficiency.

A key factor contributing to the ability to reduce the sodium hydroxide concentration to just 0.5 M or 1.0 M - while still effectively removing carbon dioxide - is the adjustment of the gas flow regime from laminar to turbulent flow. This transition increases the movement of absorbent particles in multiple directions, resulting in more frequent particle collisions and creating greater surface area exposure. These effects enhance the gas–liquid interaction, thereby improving the absorption reaction and allowing the absorbent to more effectively capture and retain carbon dioxide (Dinul et al., 2023).

A comparative summary of CO₂ removal efficiencies between the fixed bed adsorption column and the packed column scrubber, as installed and operated at full scale on a livestock farm, is provided in Table 3.

The results in Table 3 indicate that the packed column scrubber with 0.5 M sodium hydroxide as the absorbent achieved superior performance relative to the fixed-bed adsorption column. To systematically evaluate the relative performance of packed column scrubbers against other low-cost biogas upgrading technologies, a comparative assessment is presented in Table 4. The comparison focuses on key technical and economic parameters relevant to small- and medium-scale applications, thereby providing a structured basis for understanding the strengths and limitations of packed column scrubbers within the broader landscape of low-cost CO₂ removal solutions. Based on the comparative analysis, the results indicate that the packed column scrubber developed in this study offers a favorable balance between performance, cost, and operational simplicity. Its relatively low capital and operating requirements, coupled with effective CO₂ removal efficiency and ease of maintenance, make it particularly suitable for deployment in rural biogas applications. These characteristics are especially advantageous in settings where technical resources, infrastructure, and skilled labor are limited, supporting the practical implementation of biogas upgrading systems at small- to medium-scale facilities.

Table 2. Comparison of the absorption efficiency of sodium hydroxide at different concentrations

Absorbent	Biogas composition (\pm S.D.)				%CH ₄ increasing	%CO ₂ decreasing
	Before treated		After treated			
	CH ₄ (%)	CO ₂ (%)	CH ₄ (%)	CO ₂ (%)		
1 M NaOH	52.8 (\pm 0.6)	38.7 (\pm 0.5)	91 (\pm 0.8)	3.5 (\pm 0.5)	73	91
0.5 M NaOH	54.1 (\pm 0.3)	37.8 (\pm 0.7)	85 (\pm 3)	13 (\pm 3)	57	66
0.25 M NaOH	52.6 (\pm 0.5)	38.7 (\pm 0.4)	72 (\pm 4)	21 (\pm 3)	37	46

Note: Average biogas flow rate is 10–15 liters/minute.

Table 3. Biogas quality improvement of fixed bed adsorption column and packed column scrubber installed and fully operated in livestock farm

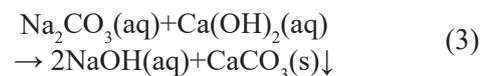
Type of treatment	Details	Adsorption / absorption material	Efficiency of biogas improvement		Biogas composition		Remarks
			%CH ₄ increasing	%CO ₂ decreasing	%CH ₄	% CO ₂	
Fixed bed adsorption column	Adsorption column with a diameter of 4 inches and a length of 1 meter, filled with NaOH-coated wood chips as an absorbent material.	3 M NaOH-coated wood chips	48	68	79.6	12.3	After 20 minutes of adsorption, the adsorption efficiency began to decrease
Packed column scrubber	4-inch diameter, 1-meter long column filled with bio-ball as an absorbent material, controlling the flow rate of NaOH 180-200 liters/hour, flowing in the opposite direction of biogas with a flow rate of 10-15 liters/minute	1 M NaOH	73	91	91	3.5	Absorption results at 30 minutes (Continuous operation for 50 minutes)
		0.5 M NaOH	57	66	85	13	Absorption results at 30 minutes (Continuous operation for 50 minutes)
		0.25 M NaOH	37	46	72	21	Absorption results at 30 minutes

Regeneration of packed column scrubber

During continuous operation of the packed column scrubber, NaOH reacts with CO₂ in the biogas stream, forming sodium bicarbonate and sodium carbonate according to Equation 2. As these carbonate species accumulate in the circulating liquid, the effective NaOH concentration decreases, leading to a gradual decline in CO₂ removal efficiency. Therefore, regeneration of the scrubbing solution is essential for sustained column performance.

Regeneration of NaOH can be achieved through a causticizing step using calcium hydroxide in a separate regeneration tank downstream of the absorber (Figure 1). In this step, the spent scrubbing solution containing Na₂CO₃ and NaHCO₃ is contacted with Ca(OH)₂, resulting in the precipitation of calcium carbonate and the simultaneous regeneration of NaOH, as described by Equation 3. The low solubility of CaCO₃ provides

the thermodynamic driving force for this reaction, effectively shifting the equilibrium toward NaOH formation.



In the presence of sodium bicarbonate, Ca(OH)₂ first converts NaHCO₃ into Na₂CO₃, which subsequently undergoes causticizing to produce NaOH. The regenerated NaOH-rich solution can then be clarified through sedimentation or filtration to remove CaCO₃ solids and recycled back to the packed column scrubber. This regeneration loop enables partial or near-complete recovery of NaOH, depending on operating conditions and stoichiometric ratios.

From a process perspective, decoupling absorption and regeneration into separate units prevents solid accumulation and fouling within the packed column, thereby preserving hydrodynamic

Table 4. Summary comparison of low-cost biogas CO₂ removal technologies

Technology	CO ₂ removal efficiency	System complexity	Energy consumption	System regeneration / maintenance	Cost level (CAPEX & OPEX)	Typical suitable applications
Water scrubbing	Medium (60–90%)	Low	Low–Medium	Easy (water degassing, simple maintenance)	Low	Community-scale and agricultural biogas plants; rural energy systems; heat and power generation where ultra-high methane purity is not required
PSA / VPSA	High (85–95%)	Medium	Medium	Medium (pressure/vacuum regeneration, adsorbent replacement)	Medium	Small-to-medium industrial biogas plants; compressed biomethane (CBG); applications requiring high and stable methane purity
Membrane separation	Medium–High (70–95%)	Medium	Medium–High	Medium–High (membrane replacement required)	Medium	Modular and space-limited installations; decentralized upgrading units; projects with relatively clean biogas and consistent operating conditions
Biological upgrading	Medium–High (80–98%)*	High	Low	High (biological stabilization and process control)	Low–Medium	Pilot-scale systems; research and demonstration projects; integrated power-to-gas or circular carbon systems
High-pressure anaerobic digestion	Low–Medium (indirect CO ₂ reduction)	Medium	Low–Medium	Low (similar to conventional digester operation)	Low–Medium	Upstream process intensification for agricultural and industrial digesters; systems aiming to reduce downstream upgrading requirements
Packed column scrubbers (in this study)	Medium–High (80–94%)	Low	Low	Low (causticizing)	Low	Community-scale and agricultural biogas plants

Note: * Efficiency strongly depends on microbial stability and process control.

performance and mass transfer efficiency. The proposed regeneration strategy not only extends the effective lifetime of the scrubbing solution but also reduces chemical consumption and operating costs, making the system more suitable for long-term biogas upgrading applications.

Overall, the NaOH–Ca(OH)₂ regeneration pathway provides a chemically robust and industrially proven approach for column regeneration, ensuring stable CO₂ removal efficiency while enabling sustainable reuse of the alkaline absorbent.

CONCLUSIONS

Carbon dioxide removal from biogas using a fixed bed adsorption column packed with sodium hydroxide-coated wood chips as the adsorbent, operating at a biogas flow rate of 10–15 L/min, achieved a carbon dioxide removal efficiency of 68%. This process increased the methane content in the biogas to 79.6(±0.9)%. However, the system’s efficiency declined noticeably after

approximately 20 minutes of continuous biogas flow. In contrast, carbon dioxide removal using a packed column scrubber with a 0.5 M sodium hydroxide solution as the absorbent achieved a 66% removal efficiency, resulting in an increase in the methane content to 85 (±3)%.

Installation and full-scale testing of both carbon dioxide removal systems at a livestock farm demonstrated that the packed column scrubber with 0.5 M sodium hydroxide is highly effective and capable of continuous operation for more than 50 minutes. Compared to the fixed bed adsorption system, it is more suitable for on-site applications due to its operational simplicity and the ability to function at atmospheric pressure, eliminating the need for additional pressurization equipment.

The upgraded biogas obtained through this method contained more than 80% methane, with an average heating value of 29.11 MJ/m³. Moreover, increasing the concentration of sodium hydroxide to 1.0 M further improved the carbon dioxide removal efficiency, resulting in a higher methane content in the biogas composition.

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