









Design and Performance of Water Scrubber and Desulfurization System for CO₂ and H₂S Purification of Biogas Produced from POME

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Abstract- This study aims to optimize the purification of biogas derived from Palm Oil Mill Effluent (POME) through a comprehensive system utilizing desulfurization and water scrubbing techniques. The primary focus is reducing the concentrations of hydrogen sulfide (H₂S) and carbon dioxide (CO₂), enhancing the quality and calorific value of methane (CH₄) in the biogas. A biogas purification system was constructed, comprising gas conditioning, water scrubber, desulfurization, and water torrents units. The system employed activated carbon and zeolite as adsorbents in the desulfurization process. Gas detection sensors were utilized to measure CH₄, CO₂, H₂S, and oxygen levels before and after purification. The analysis revealed that the purification system effectively reduced CO₂ and H₂S concentrations, Zeolite demonstrated efficient H₂S removal due to its porous nature. However, its CO₂ removal capacity was limited, possibly due to the absence of prior activation. Activated carbon, known for its strong H₂S adsorption capability, proved to be a superior adsorbent. The combination of activated carbon desulfurization, biogas conditioning, and water scrubber units optimized the removal of both H₂S and CO₂ of biogas derived from POME. The system achieved a substantial reduction in CO₂ levels, leading to a 24.54% decrease. H₂S concentrations were reduced by more than 90% through the application of activated carbon. The arrangement also ensures effective removal of H₂S before entering gas conditioning and water scrubber units, preventing equipment corrosion. This optimized purification process enhances biogas quality, elevating the calorific value of methane for various applications.

Keywords Anaerobic digestion, biogas production, desulfurization system, palm oil mill effluent, water scrubber.

1. Introduction

Palm Oil Mill Effluent (POME) is a by-product generated during the extraction of oil from Fresh Fruit Bunches (FFB) in Palm Oil Mills (POMs). This effluent is characterized by high levels of diverse organic molecules, including lipids, fatty acids, carbohydrates, nitrogenous compounds, proteins, and various minerals, as summarized in Table 1 [1-7]. Its substantial Chemical Oxygen Demand (COD) concentration makes POME a promising candidate for biogas production via anaerobic digestion.

Anaerobic digestion of POME involves a series of microbiological processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Anaerobic digestion refers to the degradation of organic compounds by anaerobic microbes in an oxygen-free environment [3], primarily producing biogas consisting of methane (CH₄) and carbon dioxide (CO₂), with minor components like hydrogen (H₂), hydrogen sulfide (H₂S), and ammonia (NH₃) [4,5,9-11]. Throughout these stages, consortia of bacteria systematically break down the complex and simple organic compounds, fatty acids, and proteins present in POME, ultimately yielding methane (CH₄) and carbon dioxide (CO₂) [1,12-14]. The efficiency of this biogas production is influenced by various factors including temperature, pH, pressure, chemical composition, mixing conditions, hydraulic retention time, nutrient availability, and the presence of inhibitory substances [1,5,15,16]. These factors collectively determine the activity and effectiveness of the microbial consortia involved in the digestion process.

The high BOD and COD concentration of POME waste and other oils makes them acceptable as raw materials for anaerobic digestion-based biogas production [13,14]. Compared to aerobic treatments, anaerobic processes exhibit slower microbial growth rates and require longer retention times. Despite this, anaerobic digestion is preferred for its cost-effectiveness and its capability to transform waste into valuable biogas [1]. This biogas, predominantly composed of methane, serves as a versatile fuel, holding significant promise in electricity generation through gas engines. Specifically, the anaerobic digestion of POME yields approximately 20 to 28 m³ of CH₄/m³ [1,17]. On average, one cubic meter of POME can produce 28 m³ of biogas [1,14]. This volume of biogas can generate about 1.8 kilowatt-hours (kWh) of energy, translating to a power generation efficiency of around 25% [1,17]. However, a by-product of this process under anaerobic conditions is hydrogen sulfide (H₂S). The genesis of H₂S primarily occurs due to sulfate-reducing bacteria that utilize sulfates (SO₄²⁻) as electron acceptors while decomposing organic compounds in the effluent. This leads to the removal of sulfur-containing molecules, predominantly proteins, and the exchange of anions, especially sulfates, under anaerobic conditions [18,17,20]. Additionally, the biochemical conversion of inorganic sulfur, particularly sulfates, further contributes to H₂S production [19].

Hydrogen sulfide poses significant environmental concerns due to its potential conversion into sulfuric acid (H₂SO₄) and toxic sulfur dioxide (SO₂), both of which are

Table 1. POME's general features of the system

Parameters	Concentration range
Temperature	80-90 °C
pH	3.4-5.2
Oil and grease	130-180,000 mg/L
Biochemical oxygen demand (BOD ₃ , 3 days incubation, 30°C)	10,250-43,750 mg/L
Chemical oxygen demand (COD)	15,000-100,000 mg/L
Total solid (SS)	11,500-79,000 mg/L
Total suspended solid (TSS)	5000-54,000 mg/L
Total volatile solid (TVS)	9000-72,000 mg/L
Total nitrogen (TN)	180-1400 mg/L
Ammoniacal nitrogen	4-80 mg/L
Colour (ADMI)	>500
Pottasium	1281-1928 mg/L
Calcium	276-405 mg/L
Magnesium	254-344 mg/L
Phosphorus	94-131 mg/L
Manganese	2.1-4.4 mg/L
Iron	75-164 mg/L
Zinc	1.2-1.8 mg/L
Copper	0.8-1.6 mg/L
Chromium	0.05-0.43 mg/L
Cobalt	0.04-0.06 mg/L
Cadmium	0.01-0.02 mg/L

detrimental to the environment and human health [21-23]. The interaction of H₂S with enzymes in the bloodstream can disrupt aerobic energy metabolism, leading to respiratory paralysis, sudden collapses, and in severe cases, death [18,24,25]. Additionally, the combustion of fuels with high H₂S concentrations increases sulfur dioxide emissions, a precursor to acid rain, causing extensive damage to vegetation and infrastructure. This gas also exhibits high toxicity, adversely affecting various machinery components, including pipes, pumps, compressors, fuel storage vessels, and engines. Moreover, it acts as a poison to liquid fuels and reformers' catalysts [18,22].

Desulfurization is recommended as an early step in the biogas upgrading process to mitigate the challenges posed by hydrogen sulfide. Effective removal of H₂S requires careful consideration of various factors, including the composition, variability, and volume of the gas to be treated, the concentration of H₂S present, and the desired reduction level of H₂S [16]. The target H₂S levels in produced biogas typically range from 0.02 to 0.05 percent by weight (200 to 500 ppm), with an H₂S-free biogas being the ideal outcome [16]. However, the specific requirements for H₂S removal vary depending on the application, equipment, and vendor specifications [26-29].

In this study, we developed a simple water scrubbing column and desulfurization system aimed at reducing the concentration of H₂S in biogas. The purification process employed water-scrubbing columns, where biogas was continuously introduced from the bottom of the column. This setup included a mixer designed to create a bubbling effect, enhancing the gas-liquid contact and thereby improving the efficiency of H₂S removal. Additionally, the biogas underwent further purification using a desulfurization system equipped with activated carbon and zeolite. These materials are known for their high adsorption capacities, making them effective in removing sulfur compounds from the gas stream. The source of biogas for this study was a biogas power plant operated by PTPN V Sei Pagar in Riau, which processes biogas produced from POME. This integrated approach combining water scrubbing and desulfurization techniques aims to effectively lower H₂S levels, thereby enhancing the quality and safety of the biogas for various applications.

2. Methodology

2.1 Biogas purification system

The biogas purification system was designed as a composite of three interconnected units: desulfurization, biogas conditioning, and water scrubbing. Each unit played a specific role in the overall purification process.

2.1.1 Desulfurization Unit

This unit employed an electric oxidation process to convert H₂S in the biogas to elemental sulfur. The primary goal was to selectively remove H₂S, thereby preventing its corrosive impact on downstream equipment. Activated carbon and zeolite were used as adsorbents in this unit, operating

under a pressure of 10 bar and a flow rate of 3 m³/hour. Activated carbon is a specially treated form of carbon with an extensive pore structure, making it an effective adsorbent for various applications, including biogas purification. Zeolite is an aluminosilicate mineral characterized by its molecular-sized pores, which make it suitable as an adsorbent material [28].

2.1.2 Biogas Conditioning Unit

Positioned downstream of the desulfurization unit, this segment focused on optimizing the biogas quality, primarily by reducing CO₂ levels, thereby aligning with global warming mitigation efforts. It consisted of three tubes of varying capacities (46 L, 76 L, and 96 L) for adjusting the pressure and flow of the biogas.

2.1.3 Water Scrubber Unit

Integrated with the biogas conditioning unit, the water scrubber operated within a pressure range of 4-10 bar and a flow rate of 3 m³/hour. It utilized a scrubbing mechanism to separate biomethane from impurities, particularly focusing on further H₂S removal. The efficiency of H₂S removal in this unit was dependent on the liquid to gas ratio.

2.2 Evaluation of biogas purification performance

A comprehensive schematic diagram illustrates the arrangement and operational flow of the interconnected units (Fig. 1). The performance of the purification system was evaluated using biogas sourced from the PTPN V Sei Pagar Riau power plant, which processes POME. Gas detection sensors were employed to measure levels of CH₄, CO₂, and H₂S before and after the purification process. The results were analyzed to assess the efficiency of activated carbon and

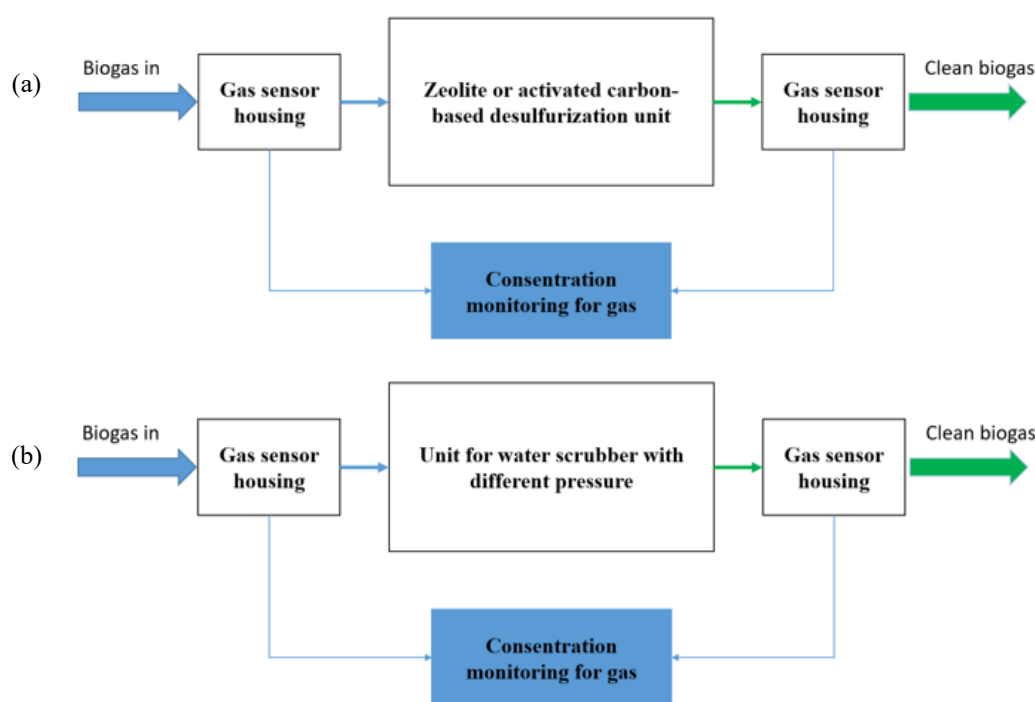


Fig. 1. Schematic of biogas purification system performance; (a) with desulfurization unit; (b) with water scrubber unit.

zeolite in removing H_2S , with a focus on comparing reduction percentages. Based on these findings, recommendations were made for an optimized purification setup, which combined desulfurization using activated carbon with the water scrubbing technique. The key parameters observed included methane, carbon dioxide, and hydrogen sulfide content, both pre- and post-purification.

3. Results and Discussions

3.1 Biogas purification system

Fig. 2 shows the biogas purification system developed by Research Centre for Energy Conversion and Conservation – BRIN, Bandung Indonesia. This system including desulfurization unit, gas conditioning unit, water scrubber unit, and water torrent.

The procedure for biogas purification in this system is described in Fig. 1. Fig. 1a presents the sampling process for evaluating the desulfurization systems. The process initiates with the assessment of biogas composition using MQ-4 and MQ-135 sensors housed within a sensor housing unit, coupled with the Geotech GA5000 portable gas analyzer for comprehensive gas analysis. Fig. 1b presents the sampling process for evaluating the water scrubber systems, which also coupled with the Geotech GA5000 portable gas analyzer for comprehensive gas analysis. In Fig. 2, Biogas (indicated by black arrows) enters the desulfurization chamber (1), constructed from galvanized steel plate, which contains adsorbing materials. The flow is generated by suction from a 2 hp air compressor (2) that feeds into a high-pressure vessel (3), reaching pressures up to 20 bar. A pressure switch is installed to regulate a solenoid valve, allowing for controlled admission of biogas into the controller vessel (4) where the pressure is maintained at 12 bar. This vessel acts as a temporary biogas storage before the gas enters the water

scrubber (5). The biogas is then introduced into (5) under variable pressures according to the test requirements. As soon as the biogas is injected into (5), a high-pressure pump (9) sprays water from the water storage (10) into (5). The filtered biogas proceeds into the tube (6) and is subsequently directed to the storage vessel (7). Meanwhile, water (indicated by transparent arrows) from the tube (5) flows into the tube (8), which is then pushed back into the water storage (12). At a certain level, an intermediary pump (11) propels the water from storage (12) to storage (10). Any excess biogas entrained with the water into tube (8) is returned to the compressor's inlet. Measurements are conducted at points before and after the desulfurization chamber (1), as well as at the outlet from the storage chamber (7). Sensors placed at the outlet of the water scrubber capture the final biogas composition for comparison against pre-treatment levels. The comprehensive data from the gas monitoring system, encompassing both pre- and post-treatment phases, are then analyzed to determine the overall performance of the purification process.

In this system Activated carbon (AC) is used in desulfurization system. AC is widely recognized for its proficiency in adsorbing low concentrations of H_2S due to its superior adsorption properties [29]. It acts not only as an adsorbent but also as a catalytic substrate, facilitating the oxidation of H_2S into elemental sulfur and sulfate. This dual function significantly boosts its efficiency in H_2S removal [30]. To achieve optimal performance, it is crucial for the AC to maintain moisture levels between 20-30% and to have an adequate supply of oxygen [31]. The findings of Sawalha et al. [34,35] corroborate the effectiveness of AC in adsorbing H_2S , highlighting its viability as a cost-effective solution for odor control and gas treatment applications. Therefore, AC can be considered a suitable option for the adsorption and removal of H_2S , providing a cost-effective solution for odor control and gas treatment applications [34].

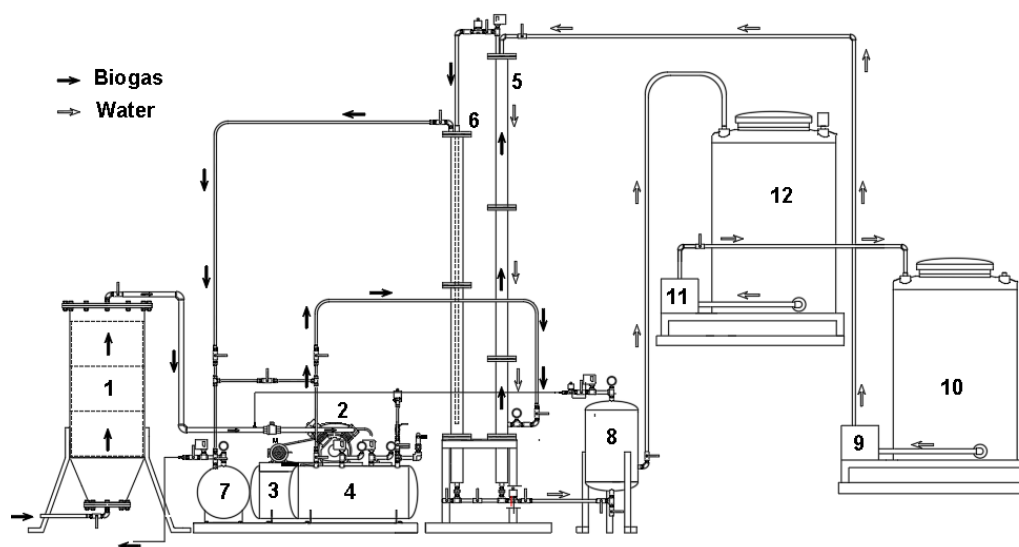


Fig. 2. Biogas purification system developed by Research Center for Energy Conversion and Conservation – BRIN. (1) desulfurized chamber, (2) air compressor, (3) high pressure vessel, (4) controller vessel, (5) water scrubber tube (6) water scrubber tube, (7) storage vessel, (8) stripping tube, (9) high pressure pump, (10) water storage, (11) intermediate pump, (12) reversible storage.

However, when it comes to CO₂ reduction, activated carbon's effectiveness is comparatively lower than that of water scrubbers. This disparity arises from the lack of chemical interaction between CO₂ and activated carbon. CO₂ removal via AC is dependent solely on its physical adsorption capacity, which is governed by the congruence of pore sizes in AC with the CO₂ molecule. In contrast, the water scrubber employs a different mechanism, where the biogas is passed through water under high pressure, leading to CO₂'s dissolution and the subsequent formation of bicarbonate ions. This process significantly enhances CO₂ removal from the gas phase. According to the Henry's law constant, which is a measure of CO₂'s solubility in water, the value is approximately 1664 atm, considerably lower than methane's (CH₄) Henry's constant of 36.600 atm [35]. This disparity underscores CO₂'s greater solubility in water, making the water scrubber a more effective method for CO₂ separation from biogas. In this study, the water scrubber unit achieved a CO₂ reduction of approximately 24.54%.

3.2 Evaluation of biogas purification performance

3.2.1 CO₂ concentration

Fig. 3 shows that the water scrubber method maintains a consistent CO₂ concentration throughout the duration of the experiment, which indicates a stable and effective removal process, likely due to the solubility of CO₂ in water and its subsequent chemical conversion to bicarbonate ions. The concentration remains around the 40% mark, suggesting that the scrubber is efficient at maintaining low CO₂ levels in the biogas. The treatment with activated carbon shows a gradual decrease in CO₂ concentration over time. This suggests that while activated carbon has some capacity to adsorb CO₂, the process is slower and less efficient compared to the water scrubber. This could be due to the physical adsorption mechanisms relying on the pore size and surface interactions,

which are less effective for CO₂ molecules compared to the water scrubber's solvation dynamics. Desulfurization with zeolite demonstrates an initial drop in CO₂ concentration, followed by a gradual downward trend. Zeolite's effectiveness can be attributed to its microporous structure, which allows for the selective adsorption of molecules based on size exclusion. However, the result suggests that zeolite is less effective than both the water scrubber and activated carbon in removing CO₂, possibly due to the non-activated state of the zeolite used. Activation of zeolites typically enhances their pore structure, thereby increasing their capacity to trap larger pollutant molecules. This suggests that the activation process plays a pivotal role in the adsorption efficacy of zeolites, particularly for molecules such as CO₂ [36]. Several studies have demonstrated the influence of zeolite activation on increasing CO₂ adsorption capacity [20, 39-43]. Notably, [39] achieved remarkable results, with CO₂ adsorption reaching 97.5% through dealumination activation using HCl and NaOH. The adsorbent's characteristics were enhanced by optimizing particle size and calcination temperature at a constant flow rate.

Based on data in Fig. 3, approximately 14.88% CO₂ reduction was obtained using water scrubber and 9,66% reduction was obtained using activated carbon desulfurizer. Combining the desulfurizer and water scrubber together might increase the CO₂ reduction to approximately 24,54%.

3.2.2 H₂S concentration

Fig. 4 delineates the H₂S concentration post-treatment with activated carbon, zeolite, and a water scrubber in desulfurization units. The marked reduction in H₂S concentration, particularly with activated carbon, is immediately apparent, with efficiencies surpassing 99%. This significant removal efficiency can be attributed to the intrinsic properties of activated carbon, such as its extensive surface

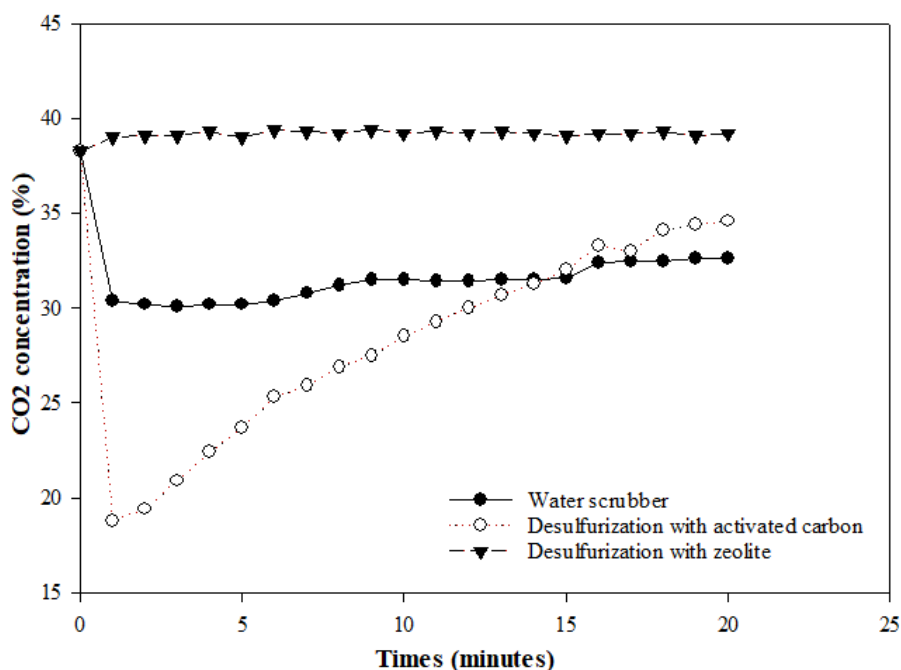


Fig. 3. CO₂ concentration after treatment using desulfurization unit with activated carbon, zeolite and water scrubber.

area and optimal pore structure, which enable robust physical adsorption coupled with potential catalytic oxidation processes. The rapid decline in H₂S levels observed in the initial phase of treatment with activated carbon shows its strong adsorptive affinity for sulfur species. This is likely facilitated by microporous regions within the carbon that are particularly conducive to capturing small H₂S molecules, hence the immediate and pronounced concentration drop.

Zeolite exhibits a more gradual decrease in H₂S concentration. This can be linked to zeolite's unique framework, composed of a regular lattice of pores that selectively sieve H₂S molecules, effectively isolating them from the biogas stream. The molecular sieve effect of zeolites is well-documented for their ability to separate gases based on molecular size exclusion, which is consistent with the trends observed in the graph. This aligns with existing literature, which acknowledges zeolite's proficiency in adsorbing H₂S due to its high porosity [36]. The mechanism behind zeolite's performance lies in its molecular structure, characterized by a network of pores that selectively adsorb various substances from gas streams, leveraging differences in molecular diameters and gas pressures [40]. The significant adsorptive interaction of zeolites with polar or polarizable molecules such as H₂S stems from their extensive surface area and the localized electric fields associated with their charged sites [41]. Adsorption onto zeolites is governed by reversible processes that may yield different structural conformations based on the strength of hydrogen bonding between the hydrogen atoms of the zeolite framework and the sulfur groups of the H₂S molecules [42].

The water scrubber's performance in H₂S removal shows a reduction in H₂S levels. The water scrubber's mechanism relies on the solubility of H₂S in water, and its less pronounced effect suggests that the conditions within the scrubber may not be as optimized for H₂S solubility as they are for CO₂. The

differential in H₂S removal performance among the three treatments is indicative of the varying degrees to which these materials and methods can physically or chemically interact with H₂S. Activated carbon stands out due to its adsorptive and potentially catalytic properties, zeolite through size-exclusion effects, and the water scrubber through solubility dynamics.

3.2.3 CH₄ concentration

Fig. 5 illustrates CH₄ concentration in biogas following treatment through desulfurization units employing activated carbon, zeolite, and a water scrubber. The data indicates that activated carbon is particularly effective in H₂S reduction, achieving a remarkable 98.44% efficiency. This high level of H₂S removal is a testament to the excellent adsorptive properties of activated carbon, which provides a large surface area for the adsorption of sulfur-containing compounds, as supported by existing literature. Conversely, zeolite's performance in CO₂ reduction was less significant, but it showed a notable capacity for H₂S removal. This is consistent with its microporous structure, which operates as a molecular sieve capable of preferentially adsorbing and thus isolating sulfur compounds. The superior H₂S adsorption by zeolite is in line with prior studies that have highlighted its unique structural properties, particularly its ability to selectively adsorb sulfur species due to the size and shape of its pores.

Moreover, the CH₄ concentration trends depicted in the graph provide insights into the selective separation capabilities of the different adsorbents. While the concentration of CH₄ slightly decreases in the presence of activated carbon and zeolite, likely due to their adsorption of other components from the biogas, the water scrubber maintains a relatively stable CH₄ concentration. This stability suggests that the water scrubber is less selective in the

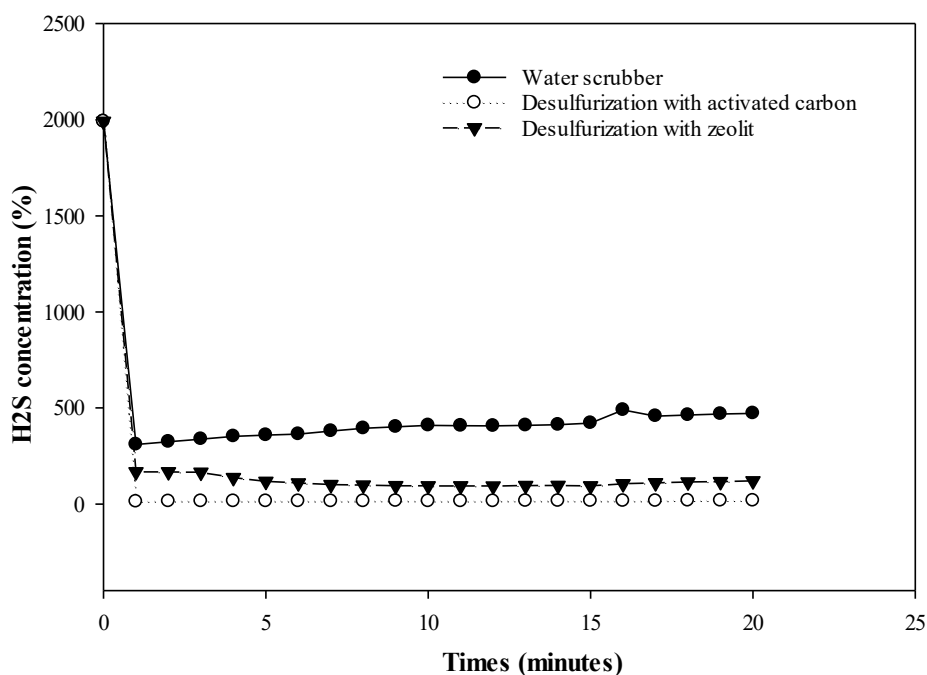


Fig. 4. H₂S concentration after treatment using desulfurization unit with activated carbon, zeolite and water scrubber.

compounds it removes, primarily targeting CO₂ over CH₄, thus preserving the calorific value of the biogas.

3.2.4 Greenhouse gas emission reduction

The conversion of POME to biogas inherently contributes to greenhouse gas emission reduction by capturing methane, which would otherwise be naturally released if POME were left untreated. The potential CH₄ emission from POME is about 42.4 m³ CH₄/ton POME, equivalent to 0.779 metric tons of CO₂ in terms of Global Warming Potential (GWP) over 100 years [39]. In our study, the CH₄ content in biogas from POME was 59.1%, and the CO₂ content was 38.3%. The reduction in CO₂ content from purification using the combination of desulfurizer and water scrubber was 24.54% [40], which could lead to a potential decrease in greenhouse gas emissions from CO₂ purification in POME-based biogas to about 0.0121 metric tons CO₂/ton POME [41]. Combining CH₄ capture through biogas production from POME and CO₂ purification using a hybrid system with a water scrubber has the potential to reduce the GWP by approximately 0.791 metric tons of CO₂/ton POME.

3.3 Optimization Recommendation

The findings from this research propose an optimized strategy for biogas purification. The recommendation is the incorporation of a desulfurization unit with activated carbon, followed by biogas conditioning unit, and finally water scrubber, to achieve maximal removal of H₂S and CO₂. The combination of a desulfurizer and water scrubber is still advantageous, as it does not significantly increase investment costs. This is because, to increase the methane content in biogas to biomethane levels (CH₄ content > 91%), a CO₂ removal unit is inevitably required in the biogas purification system. Given the high CO₂ content in biogas (ranging from 15% to 60%) [6], a CO₂ removal unit is essential for producing biomethane. The increase in investment costs may stem from the desulfurization unit, although these costs are likely not too

high compared to the water scrubber. Activated carbon, used as an adsorbent, can be reused through regeneration processes, thus not significantly increasing operational costs. The combination of a desulfurization unit and water scrubber, equipped with gas conditioning, could potentially enhance the value of biogas produced from anaerobic digestion. Detailed design parameters and further economic feasibility studies are needed, paving the way for large-scale biogas purification equipment design in future research.

Given previous research highlighting zeolite's capacity for CO₂ and possibly H₂S adsorption, further exploration of zeolite as an adsorbent with activation processes could be an alternative to using activated carbon in the desulfurization unit. This could also serve as an initial treatment to reduce CO₂ levels before entering the water scrubber, potentially yielding higher CH₄ content in biogas. Future studies should also focus on the mass of adsorbent used, variations in biogas flow rate, and adsorption kinetics to determine adsorption capacity and necessary breakthrough curves for designing biogas desulfurization equipment. For the water scrubber, it is essential to confirm the solubility and diffusivity values of CO₂ in water from literature with experimental data at various biogas flow rates is crucial for scaling up the water scrubber unit [43]. This approach will produce design data applicable to large-scale installations, aiding in overcoming scalability and applicability challenges. For large-scale installations, alongside design variables, an economic analysis is necessary to ensure the sustainability of the application in biogas plants using POME as feedstock.

The current utilization of biogas is limited due to challenges in storage and transportation. Cryogenic processes for biogas liquefaction require high pressures and extremely low temperatures, leading to substantial costs [6]. High-pressure biogas packaging is also hindered by high impurity levels, particularly CO₂, necessitating additional storage space. Pipeline distribution requires high methane purity. Nowadays, there's an increasing focus on purifying biogas into

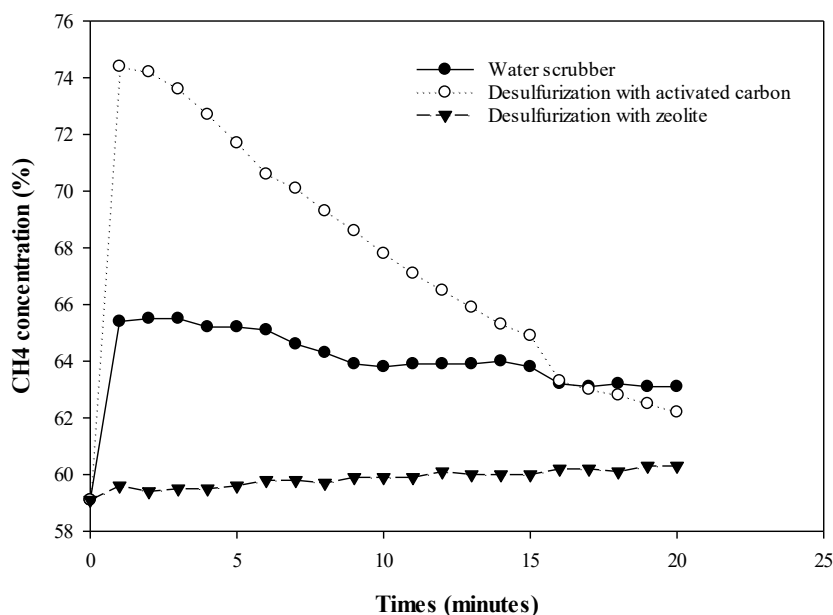


Fig. 5. CH₄ concentration after treatment using desulfurization unit with activated carbon, zeolite and water scrubber.

biomethane with a CH₄ content above 91%, making it marketable. Purifying biogas to achieve high methane levels ensures the sustainable application of biogas technology for organic waste treatment, renewable energy generation, and diverse applications.

4. Conclusion

In conclusion, this study investigated the efficacy of an integrated biogas purification system, comprising a desulfurization unit, a biogas conditioning unit, and a water scrubber, for treating biogas derived from Palm Oil Mill Effluent (POME). The study concludes that employing a sequential integration of an activated carbon-based desulfurization unit, followed by biogas conditioning and culminating with a water scrubber, constitutes an optimal purification strategy. This configuration achieved a significant CO₂ reduction of 24,54% and an H₂S concentration decrease of over 90%. To prevent the corrosion of equipment and to ensure the maintenance of optimal gas pressures, a hybrid system is advocated. This system positions the desulfurization unit upstream to protect downstream components, with the water scrubber situated downstream to maximize CO₂ extraction. Implementing this comprehensive purification approach will enhance the overall quality of biogas, rendering it more suitable for a myriad of applications.

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Declarations

Author contribution

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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References

- [1] E. I. Ohimain and S. C. Izah, "A review of biogas production from palm oil mill effluents using different configurations of bioreactors," *Renew. Sustain. Energy Rev.*, vol. 70, pp. 242–253, Apr. 2017, doi: 10.1016/j.rser.2016.11.221.
- [2] M. M. Bello, M. M. Nourouzi, L. C. Abdullah, T. S. Y. Choong, Y. S. Koay, and S. Keshani, "POME is treated for removal of color from biologically treated POME in fixed bed column: Applying wavelet neural network (WNN)," *J. Hazard. Mater.*, vol. 262, pp. 106–113, Nov. 2013, doi: 10.1016/j.jhazmat.2013.06.053.
- [3] A. Wresta, R. Widyarani, R. Boopathy, and T. Setiadi, "Thermodynamic approach to estimating reactions and stoichiometric coefficients of anaerobic glucose and hydrogen utilization," *Eng. Reports*, vol. 3, no. 6, Jun. 2021, doi: 10.1002/eng2.12347.
- [4] M. A. Salamanca-Valdivia, L. Cardenas-Herrera, J. E. Barreda-Del-Carpio, G. M. Moscoso-Apaza, R. E. Garate-de-Davila, and C. A. Munive-Talavera, "Production of biogas in a dry anaerobic digestion reactor of residues generated in the processing of sheep and alpaca wool," in *2021 10th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2021, pp. 152–154. doi: 10.1109/ICRERA52334.2021.9598668.
- [5] M. K. Md. Azizul Haque, AKM Ahsan Kabir, Md. Abul Hashem, Md. Abul Kalam Azad and M. M. R. Jaman Bhuiyan, "Efficacy of Biogas Production from Different Types of Livestock Manures," *Int. J. Smart grid*, Dec. 2021, doi: 10.20508/ijsmartgrid.v5i4.215.g177.
- [6] D. Andriani, A. Wresta, T. D. Atmaja, and A. Saepudin, "A Review on Optimization Production and Upgrading Biogas Through CO₂ Removal Using Various Techniques," *Appl. Biochem. Biotechnol.*, vol. 172, no. 4, pp. 1909–1928, Feb. 2014, doi: 10.1007/s12010-013-0652-x.
- [7] E. Ohimain and S. Izah, "Possible Contributions of Palm Oil Mill Effluents to Greenhouse Gas Emissions in Nigeria," *Br. J. Appl. Sci. Technol.*, vol. 4, no. 33, pp. 4705–4720, Jan. 2014, doi: 10.9734/BJAST/2014/10698.
- [8] B. Trisakti, V. Manalu, I. Taslim, and M. Turmuzi, "Acidogenesis of Palm Oil Mill Effluent to Produce Biogas: Effect of Hydraulic Retention Time and pH," *Procedia - Soc. Behav. Sci.*, vol. 195, pp. 2466–2474, Jul. 2015, doi: 10.1016/j.sbspro.2015.06.293.
- [9] L. Guerrero, F. Omil, R. Méndez, and J. M. Lema, "Anaerobic hydrolysis and acidogenesis of wastewaters from food industries with high content of organic solids and protein," *Water Res.*, vol. 33, no. 15, pp. 3281–3290, Oct. 1999, doi: 10.1016/S0043-1354(99)00041-X.
- [10] Y. Ahmed, Z. Yaakob, P. Akhtar, and K. Sopian, "Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME)," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 1260–1278, Feb. 2015, doi: 10.1016/j.rser.2014.10.073.
- [11] D. Karakashev, D. J. Batstone, and I. Angelidaki, "Influence of Environmental Conditions on Methanogenic Compositions in Anaerobic Biogas Reactors," *Appl. Environ. Microbiol.*, vol. 71, no. 1, pp. 331–338, Jan. 2005, doi: 10.1128/AEM.71.1.331-338.2005.
- [12] M. K. C. Sridhar and O. O. AdeOluwa, "Palm Oil Industry Residues," in *Biotechnology for Agro-Industrial Residues Utilisation*, Dordrecht: Springer Netherlands, 2009, pp. 341–355. doi: 10.1007/978-1-4020-9942-7_18.

- [13] K. W. Kan, Y. J. Chan, T. J. Tiong, and J. W. Lim, "Maximizing biogas yield from palm oil mill effluent (POME) through advanced simulation and optimisation techniques on an industrial scale," *Chem. Eng. Sci.*, vol. 285, p. 119644, Mar. 2024, doi: 10.1016/j.ces.2023.119644.
- [14] Y. Ulusoy and A. H. Ulukardesler, "Biogas production potential of olive-mill wastes in Turkey," in 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), Nov. 2017, pp. 664–668. doi: 10.1109/ICRERA.2017.8191143.
- [15] B. Khoshnevisan, P. Tsapekos, N. Alfaro, I. Diaz, M.F. Polanco, S. Rafiee, and I. Angelidaki, "A review on prospects and challenges of biological H₂S removal from biogas with focus on biotrickling filtration and microaerobic desulfurization," *Biofuel Res. J.*, vol. 4, no. 4, pp. 741–750, Dec. 2017, doi: 10.18331/BRJ2017.4.4.6.
- [16] I. Ramos and M. Fdz-Polanco, "The potential of oxygen to improve the stability of anaerobic reactors during unbalanced conditions: Results from a pilot-scale digester treating sewage sludge," *Bioresour. Technol.*, vol. 140, pp. 80–85, Jul. 2013, doi: 10.1016/j.biortech.2013.04.066.
- [17] A. J. M. Stams, S. J. W. H. O. Elferink, and P. Westermann, "Metabolic Interactions Between Methanogenic Consortia and Anaerobic Respiring Bacteria," 2003, pp. 31–56. doi: 10.1007/3-540-45839-5_2.
- [18] X. Liu, Y. Inbar, P.C. Dorrestein, C. Wynne, N. Edwards, P. Souda, J.P. Whitelegge, V. Bafna, and P.A. Pevzner, "Deconvolution and Database Search of Complex Tandem Mass Spectra of Intact Proteins," *Mol. Cell. Proteomics*, vol. 9, no. 12, pp. 2772–2782, Dec. 2010, doi: 10.1074/mcp.M110.002766.
- [19] O. W. Awe, Y. Zhao, A. Nzihou, D. P. Minh, and N. Lyczko, "A Review of Biogas Utilisation, Purification and Upgrading Technologies," *Waste and Biomass Valorization*, vol. 8, no. 2, pp. 267–283, Mar. 2017, doi: 10.1007/s12649-016-9826-4.
- [20] K. Tang, V. Baskaran, and M. Nemati, "Bacteria of the sulphur cycle: An overview of microbiology, biokinetics and their role in petroleum and mining industries," *Biochem. Eng. J.*, vol. 44, no. 1, pp. 73–94, Apr. 2009, doi: 10.1016/j.bej.2008.12.011.
- [21] W. Zhou, T. Imai, M. Ukita, F. Li, and A. Yuasa, "Effect of limited aeration on the anaerobic treatment of evaporator condensate from a sulfite pulp mill," *Chemosphere*, vol. 66, no. 5, pp. 924–929, Jan. 2007, doi: 10.1016/j.chemosphere.2006.06.004.
- [22] G. Rodriguez, A. D. Dorado, M. Fortuny, D. Gabriel, and X. Gamisans, "Biotrickling filters for biogas sweetening: Oxygen transfer improvement for a reliable operation," *Process Saf. Environ. Prot.*, vol. 92, no. 3, pp. 261–268, May 2014, doi: 10.1016/j.psep.2013.02.002.
- [23] S. E. Hosseini and M. A. Wahid, "Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 454–462, Mar. 2013, doi: 10.1016/j.rser.2012.11.008.
- [24] T. Las and H. Zamroni, "Application of Zeolite in Industries and Environments," *J. Zeolit Indones.*, pp. 23–30, 2002, [Online]. Available: <http://journals.itb.ac.id/index.php/jzi/article/view/1646>
- [25] S. Zhang, Q. Chen, M. Hao, Y. Zhang, X. Ren, F. Cao, L. Zhang, and Q. Sun, "Effect of functional groups on VOCs adsorption by activated carbon: DFT study," *Surf. Sci.*, vol. 736, p. 122352, Oct. 2023, doi: 10.1016/j.susc.2023.122352.
- [26] D. H. Romero, D. Icaza, and J. Gonzalez, "Technical - Economic Study for the Implementation of Solar Energy in the Presence of Biomass and Micro Hydraulic Generation, for Sectors that do not Have Electricity Supply in the Province of Bolivar-Ecuador," in 2019 7th International Conference on Smart Grid (icSmartGrid), Dec. 2019, pp. 149–154. doi: 10.1109/icSmartGrid48354.2019.8990865.
- [27] M. Chowdhury, S., Hossan, A., Semel, S. A., and Zhou, "Hydrogen Energy Storage Based Biogas Power Plant in Bangladesh: Design and Optimal Cost Analysis," in 2022 10th International Conference on Smart Grid (icSmartGrid), Jun. 2022, pp. 35–39. doi: 10.1109/icSmartGrid55722.2022.9848560.
- [28] T. Laz and H. Zamroni, "Penggunaan Zeolit dalam Bidang Industri dan Lingkungan," *J. Zeolit Indones.*, vol. 1, no. 1, pp. 23–30, 2002.
- [29] H. Ji, Z. Liu, X. Xie, W. Jiang, S. Wan, B. Wang and X. Xiang, "Norfloxacin removal efficiency by a carbon filtration column under the influence of nanoplastics: mechanistic analysis and prediction model," *Water Supply*, vol. 23, no. 5, pp. 2105–2118, May 2023, doi: 10.2166/ws.2023.108.
- [30] B. Bunker, B. Dvorak, and A. Aly Hassan, "Thermal Regeneration of Activated Carbon Used as an Adsorbent for Hydrogen Sulfide (H₂S)," *Sustainability*, vol. 15, no. 8, p. 6435, Apr. 2023, doi: 10.3390/su15086435.
- [31] S. Perry, R. H. Perry, D. W. Green, and J. O. Maloney, "Perry's chemical engineers' handbook," *Choice Rev. Online*, vol. 38, no. 02, pp. 38–0966–38–0966, Oct. 2000, doi: 10.5860/CHOICE.38-0966.
- [32] H. S. Tira and Y. A. Padang, "Removal of CO₂ and H₂S from raw biogas using activated natural zeolite," 2016, p. 030006. doi: 10.1063/1.4965740.
- [33] M. Cavallo, M. Dosa, N. G. Porcaro, F. Bonino, M. Piumetti, and V. Crocellà, "Shaped natural and synthetic zeolites for CO₂ capture in a wide temperature range," *J. CO₂ Util.*, vol. 67, p. 102335, Jan. 2023, doi: 10.1016/j.jcou.2022.102335.
- [34] M. M. Lakapu and N. Widiastuti, "Synthesis of Zeolite-X Supported on Kapok Fiber for CO₂ Capture Material:

- Variation of Immersion Time during Fiber Activation,” *Indones. J. Chem.*, vol. 17, no. 3, p. 471, Nov. 2017, doi: 10.22146/ijc.25162.
- [35] E. Indriani, D. Hardi, and Purnomosidi, “Zeolite and Active Carbon as Contacting Media for CO₂ Removal: Case study - CO₂ Removal of Produced Gas at PT Pertamina EP Asset XY,” 2021. doi: 10.2991/aer.k.210810.049.
- [36] W.W. Lestari, L. Yunita, T.E. Saraswati, E. Heraldly, M. A. Khafidhin, U.S.F. Arrozi and T.M. Grandprix, “Fabrication of composite materials MIL-100(Fe)/Indonesian activated natural zeolite as enhanced CO₂ capture material,” *Chem. Pap.*, vol. 75, no. 7, pp. 3253–3263, Jul. 2021, doi: 10.1007/s11696-021-01558-2.
- [37] I. G. B. N. Makertihartha, P. T. Dharmawijaya, M. Zunita, and I. G. Wenten, “Post combustion CO₂ capture using zeolite membrane,” 2017, p. 020074. doi: 10.1063/1.4979941.
- [38] C. Xiao, Y. Ma, D. Ji, and L. Zang, “Review of desulfurization process for biogas purification,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 100, p. 012177, Dec. 2017, doi: 10.1088/1755-1315/100/1/012177.
- [39] P. Herlian Eriska, A. Wresta, D. Permana, Djaenudin, F. Dara, L. Indriati, Muchlis, N. Sintawardani, N. Fitria, U. Hamidah, and W. Purwanta, “Hydrothermal treatment of empty fruit bunches for enhanced solid fuel production using palm oil mill effluent as a liquid stream,” *Bioresour. Technol. Reports*, vol. 25, p. 101761, Feb. 2024, doi: 10.1016/j.biteb.2024.101761.
- [40] A. Manmeen, P. Kongjan, T. Rattanaya, B. Cheirsilp, N. Raybut, and R. Jariyaboon, “Desulfurization of H₂S-rich biogas using water scrubbing: Performance in pilot scale scrubber and scale-up estimation for the concentrated latex factory,” *Environ. Prog. Sustain. Energy*, vol. 42, no. 3, May 2023, doi: 10.1002/ep.14034.
- [41] F. C. Suci, “Rancang Bangun Alat Purifikasi Biogas Water Scrubber Berbasis Mikrokontroler,” *J. Poli-Teknologi*, vol. 19, no. 2, pp. 151–160, Nov. 2020, doi: 10.32722/pt.v19i2.2804.
- [42] A. Starke, C. Pasel, C. Bläker, T. Eckardt, J. Zimmermann, and D. Bathen, “Investigation of the Adsorption of Hydrogen Sulfide on Faujasite Zeolites Focusing on the Influence of Cations,” *ACS Omega*, vol. 7, no. 48, pp. 43665–43677, Dec. 2022, doi: 10.1021/acsomega.2c04606.
- [43] G. R. Mugagga, I. B. Omosa, and T. Thoruwa, “Optimization and Analysis of a Low-Pressure Water Scrubbing Biogas Upgrading System via the Taguchi and Response Surface Methodology Approaches,” *Int. J. Renew. Energy Dev.*, vol. 12, no. 1, pp. 99–110, Jan. 2023, doi: 10.14710/ijred.2023.48269.