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EXPERIMENTAL ANALYSIS OF HYDROGEN SULFIDE REMOVAL FROM BIOGAS USING A BIOFILTER CONTAINING CELLULAR CONCRETE WASTE AND BIOCHAR

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Abstract. This study investigates the removal efficiency of hydrogen sulfide (H_2S) from biogas using a biofilter packed with cellular lightweight concrete (CLC) waste and biochar. A laboratory-scale biofilter was designed and tested under varying operational and environmental conditions, including inlet H_2S concentrations (100–2000 ppm), gas flow rates (0.2–1.0 L/min), temperature (25–35 °C), and humidity (70–90%). The results demonstrated that H_2S removal efficiency reached 95% at low air flow rates and 91% under low H_2S concentrations. In comparison, efficiency declined to 88% at high air flow rates and 87% at high H_2S concentrations. The combination of biochar's adsorption properties and Fe_2CO_3-modified CLC waste's catalytic oxidation contributed to the biofilter's high efficiency and stability. These findings suggest that hybrid biofilters incorporating waste-derived materials provide an environmentally sustainable and cost-effective alternative for biogas purification compared to conventional chemical and physical methods.

Keywords: hydrogen sulfide removal, biofilter, biochar, cellular concrete (CLC) waste, microbial desulfurization, biogas purification.

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1. Introduction

Biogas purification is a critical process in renewable energy applications, as contaminants such as hydrogen sulfide (H_2S) can severely impact equipment integrity, efficiency, and environmental compliance. Biogas typically contains 100–20,000 ppm of H_2S, depending on the feedstock composition and anaerobic digestion conditions (Alkhatib et al., 2021). High concentrations of H_2S can lead to corrosion of equipment, environmental pollution, and decreased biogas energy value (Appala et al., 2022). Desulfurization is essential to lower H_2S concentrations before biogas utilization. Conventional H_2S removal technologies, including chemical and physical adsorption methods, often involve high costs and environmental concerns (Bu et al., 2021). Biofiltration has emerged as a promising alternative due to its sustainability, cost-effectiveness, and ability to support microbial activity for contaminant removal (González-Cortés et al., 2021).

Biofiltration is a process that uses a packed bed system to treat contaminated gas streams by passing them through a bed of porous materials colonized by microorganisms (Choudhury & Lansing, 2021). In the context of H_2S removal, biofilters combine physical adsorption and biological oxidation to achieve efficient desulfurization. This study focuses on two packing materials: sewage sludge-derived biochar pyrolyzed at 600 °C, and cellular lightweight concrete (CLC) waste, which represent organic and inorganic materials, respectively (Santos-Clotas et al., 2020). These materials were chosen based on their cost-effectiveness, availability, and potential for modification to enhance H_2S removal efficiency in the biofilter (Cano et al., 2021).

This study explores the feasibility of using a biofilter packed with a configuration of CLC waste and biochar to remove H_2S from biogas streams. Throughout the study, the impact of environmental and operational conditions, including but not limited to 1) Inlet Loading Rate (ILR), which is a crucial parameter in biofiltration, representing the mass of H_2S introduced into the biofilter per unit volume of packing material per unit time (Danila et al., 2022). It is influenced by H_2S concentration in the inlet gas stream (ppm) and biogas flow rate (L/min) (De Souza et al., 2021). ILR directly affects the removal efficiency (RE) of H_2S and the performance of microbial communities involved in biological desulfurization (Das et al., 2022). 2) Initial H_2S concentration in raw biogas before injecting into the biofilter (Ghimire et al., 2021). Higher inlet H_2S concentrations pose challenges in adsorption, microbial oxidation, and mass transfer within the biofilter, affecting overall removal efficiency (Haosagul et al., 2020). 3) Temperature inside the biofilter: A crucial parameter that plays a vital role in supporting the Sulfur Oxidizing

Bacteria (SOB) (Santos-Clotas et al., 2020). 4) Moisture content (known as humidity) of the packing materials: This factor must be controlled throughout the analysis to maintain the best performance of the SOBs to desulfurize H_2S from biogas and reach higher removal efficiency (RE) (Haosagul et al., 2020).

2. Materials and methods

This study focuses on a biofilter divided into 6 stages, packed with CLC waste (particles in 11 cm diameter and up to 547 kg/m^3 density) and sewage sludge-derived biochar (particles in 0.6 mm to 1 cm, mass of 130–190 g, and density of up to 80 kg/m^3), and altering the physical and chemical properties to improve their efficiency and sorption capacity. The modifications involve activating biochar with potassium hydroxide (KOH) and impregnating CLC waste with iron carbonate (Fe_2CO_3) to enhance adsorption. These modifications are evaluated to determine their effect on biofilter performance under different operational conditions. The environmental and operational conditions of the whole process are controlled by the Testo 400 kit tool (to control the temperature and gas flow rate inside the biofilter), Gas Data Analyzer (GDA) (to monitor the level of H_2S concentrations at each stage of the biofilter), and an automatic irrigation system to control the level of sprayed nutrient solution together with deionized water (controlling level of humidity in system) that are vital for microbial growth.

The study utilized a custom-designed, laboratory-scale biofilter system to replicate real-world biogas purification processes. The biofilter column was made of transparent acrylic, measuring 14 cm in internal diameter and 1 m in height, allowing for clear visualization and monitoring of gas flow and material packing. Each biofilter was equipped with gas sampling ports at the inlet, midsection, and outlet to track H_2S concentrations and other key parameters throughout the column. A plate at the base ensured uniform biogas distribution through the packing material, while a gas flowmeter maintained a controlled and consistent flow rate for reproducible experimental conditions. Combining biochar and CLC waste, hybrid configurations were tested to explore potential synergies in adsorption and biological oxidation (Jiang et al., 2020). Layered arrangements were employed to optimize adsorption efficiency and microbial activity distribution (Jedynak & Charmas, 2023). The biofilters were evaluated under varying operational conditions to assess their effectiveness and stability in H_2S removal (Khan et al., 2021). Figure 1 below shows the structure of a laboratory-scale biofilter, how the H_2S concentration and biogas are injected into the biofilter by balloons, the stages of the packing materials, and the gauges to evaluate the operational and environmental conditions of the system.

Raw biochar was treated with KOH to enhance porosity and adsorption capacity. First started with soaking biochar in a KOH solution to introduce functional groups that improve H_2S binding sites (Lee et al., 2021). Then, heat activation at controlled temperatures (typically around 300–700 °C) to increase surface area and reactivity. Finally, wash and dry them to remove excess chemicals while preserving the microporous structure (Lin et al., 2021). There are some reasons: a) Raw biochar has a limited surface area for H_2S adsorption. b) KOH activation increases porosity, allowing more H_2S molecules to bind. c) Enhanced adsorption properties lead to higher H_2S removal efficiency. CLC waste was impregnated Fe_2CO_3 to improve the catalytic oxidation of H_2S (Mohammadi & Vaiškūnaitė, 2023). First, CLC waste is soaked in Fe_2CO_3 solution to introduce reactive iron-based

Figure 1. Lab-scale biofilter structure and main components

compounds. Then, the drying and curing process takes place to ensure strong binding of Fe_2CO_3 to the CLC structure. Finally, testing the material to confirm efficiency in H_2S oxidation (Mitchell et al., 2022). There are some reasons: a) Raw CLC waste lacks strong catalytic properties. b) Iron carbonate enhances oxidation reactions, converting H_2S into elemental sulfur or sulfate. c) Combining adsorption (biochar) with oxidation (CLC waste) improves overall biofilter performance (Nhut et al., 2020).

Gas sampling ports at the inlet, midsection, and outlet were used to monitor concentration variations of H_2S. Inlet H_2S concentrations were chosen to be (100–2000 ppm) to simulate real-world biogas compositions, where H_2S levels fluctuate based on feedstock composition and anaerobic digestion conditions. It also allowed an evaluation of how different H_2S loads impact removal efficiency and microbial adaptation (Pudi et al., 2022). Flow rates (0.2–1.0 L/min): Flow rates were adjusted to assess the effect of gas residence time on biofilter performance (Poser et al., 2023). Lower flow rates (0.2–0.5 L/min) enhanced H_2S adsorption and microbial oxidation, whereas higher rates (above 0.8 L/min) tested the biofilter's capacity under high-loading conditions (Shi et al., 2022). Temperature (25–35 °C): This range was selected based on optimal growth conditions for Thiobacillus sulfur-oxidizing bacteria (SOBs), which play a crucial role in biological H_2S removal (Talaiekhozani et al., 2017). Biofilter efficiency decreases outside this temperature range due to reduced microbial metabolism (Torres et al., 2020). Humidity (70–90%): Maintaining appropriate moisture content in the packing materials was critical to supporting biofilm formation and preventing desiccation of SOBs (Vaiškūnaitė, 2020). Variations in humidity allowed an assessment of how moisture fluctuations impact microbial activity and H_2S oxidation. Moisture levels were maintained between 70–90% using a nutrient solution (1 L deionized water + K_2HPO_4 (0.02 g) + $(NH_4)_2SO_4$ (0.08 g) + Na_2CO_3 (0.39 g)) (Wang et al., 2022).

3. Results and discussions

The combination of biochar and CLC waste was evaluated to assess its performance in hydrogen sulfide (H_2S) removal. This hybrid configuration aimed to leverage the adsorption and microbial-support properties of biochar and the adsorption properties of Fe_2CO_3-modified CLC waste. The biochar + CLC waste configuration demonstrated an acceptable H_2S removal efficiency (≈96%) under optimal conditions. Biochar provides high adsorption capacity for H_2S due to its microporous structure and functional groups (e.g., hydroxyl and carboxyl) (Watsuntorn et al., 2020). Fe_2CO_3-modified CLC waste facilitated the adsorption oxidation of H_2S into elemental sulfur and sulfate, enhancing the overall efficiency of the biofilter (Wu et al., 2020). The interaction between the materials prevented saturation of adsorption sites, as oxidation on CLC waste regenerated biochar's active sites (Xia et al., 2019). Table 1 below illustrates the detected level of H_2S concentrations (ppm), 6 days after the initial injection of the biogas into the system, at different stages and operational conditions.

Combining biochar and CLC waste created a balanced environment supporting adsorption-based and microbial-driven H_2S removal. Microbial populations were more evenly distributed along the biofilter. As stated before, 6 days after the initial injection of raw biogas into the biofilter, this configuration consistently achieved a high RE, driven by the synergy between adsorption and biofiltration

Table 1. H_2S concentration monitoring after injecting biogas into the biofilter packed with biochar + CLC waste

	Low flow rates	High flow rates	Low to moderate H_2S concentrations	High H_2S concentrations
H_2S concentrations (ppm) after an hour				
All stages	90	100	630	1050
H_2S concentrations (ppm) after 3 days				
1st stage	990	70	450	710
2nd stage	220	30	180	300
3rd stage	110	10	80	90
4th stage	110	10	30	40
5th stage	0	10	20	30
6th stage	0	0	10	20
H_2S concentrations (ppm) after 6 days				
1st stage	60	30	170	370
2nd stage	20	20	60	150
3rd stage	10	10	40	60
4th stage	0	0	10	20
5th stage	0	0	10	10
6th stage	0	0	0	0

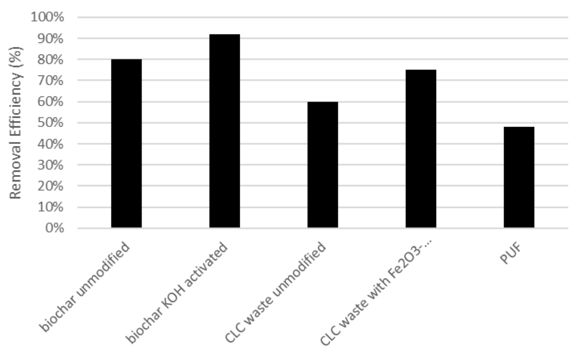

Figure 2. Comparison of biofilter RE of H_2S from biogas, at different operational conditions

mechanisms. The porous structure of CLC waste prevented rapid saturation of biochar's adsorption sites, enhancing the system's longevity. However, the modification of CLC waste with Fe_2CO_3 involves additional processing steps, increasing the initial material cost. Figure 2 above shows the hydrogen sulfide removal efficiencies of the biofilter packed with biochar and CLC waste at different operational conditions.

- At lower airflow rates (RE = 95% efficiency), the residence time of the biogas in the biofilter increases, allowing for greater adsorption of H_2S onto biochar and CLC waste. Higher air flow rates (RE = 88% efficiency) reduce contact time, leading to less adsorption and microbial oxidation per unit of gas processed. This result indicates that at high flow rates, the system may reach mass transfer limitations, restricting the diffusion of H_2S into the biofilm where microbial oxidation occurs. The biofilter operates more efficiently at lower airflow rates because of improved adsorption and enhanced microbial processing time.
- At lower ILRs (100–500 ppm, 0.2 L/min flow rate), higher REs (above 90%) was achieved, indicating that the biofilter had sufficient microbial capacity and surface area for adsorption and biological oxidation. At moderate ILRs (500–1000 ppm, 0.5 L/min flow rate), RE remained stable but declined slightly (~80%) due to increased competition for active sites in the biofilter. At higher ILRs (1000–2000 ppm, 1.0 L/min flow rate), RE decreased significantly (down to ~65%) as the biofilter became saturated with H_2S, microbial activity struggled to keep up, and mass transfer limitations became apparent. Sulfur-oxidizing bacteria (SOBs) activity is influenced by ILR because lower ILR allows for stable biofilm formation and optimal microbial oxidation of H_2S. Higher ILR leads to substrate inhibition, where excess H_2S becomes toxic to microbial communities.
- At low to moderate H_2S concentrations (100–500 ppm), RE reached 91% efficiency; the biofilter materials (biochar and CLC waste) do not become saturated as quickly, maintaining a high adsorption capacity. The microbial community is less stressed, leading to a more stable oxidation process (Xu et al., 2022). At high H_2S concentrations (>1500 ppm), RE reached 87% efficiency, and the adsorption sites on biochar became saturated more quickly, reducing the effectiveness of physical H_2S capture. The increased sulfur load may also inhibit microbial activity, as excess H_2S can lead to acidic conditions, negatively affecting the growth and function of sulfur-oxidizing bacteria (SOBs) (Ying et al., 2020). The biofilter performed slightly better at lower H_2S concentrations due to less stress on microbial communities and less frequent adsorption site saturation.
- Temperatures around 25–30 °C showed the optimal range for microbial activity, ensuring high H_2S removal efficiency (85–92%). When increased to 30–35 °C, a moderate decline in efficiency (~80%) is due to increased biofilm metabolism, but potential microbial stress is detected (Zhang et al., 2021). However, above 35 °C, RE dropped below 70%, as high temperatures negatively affected microbial stability and mass transfer rates (Zhang et al., 2022).
- Higher humidity (~85–90%) enhanced H_2S removal efficiency (85–95%), ensuring optimal biofilm formation for sulfur-oxidizing bacteria (SOBs). While lower humidity (<70%) led to a decline in removal efficiency (~65%) due to biofilm drying and reduced microbial activity. The optimal moisture range was 75–85%, as best microbial growth and high biofilter efficiency were detected (Zhanga et al., 2020). Overall, maintaining a continuous moisture supply was critical for biofilter efficiency, particularly for CLC waste and microbial activity.

4. Conclusions

- Optimal RE performance (95%) is observed at low flow rates, where adsorption and microbial activity are maximized. At higher flow rates the RE (88%) limits residence time, decreasing the efficiency of physical and biological H_2S removal. At high H_2S concentrations, RE (87%) reduces efficiency due to biofilter material saturation and microbial inhibition. At lower H_2S concentrations RE reached 91%, and microbial activity is more stable, resulting in slightly better removal efficiency than at high concentrations.
- The optimal operational temperature for the biofilter was 25–30 °C, ensuring stable microbial growth and efficient H_2S removal. Maintaining temperature control below 35 °C was critical to avoid microbial inhibition and loss of adsorption efficiency. Cooling mechanisms or temperature-controlled biofilters could enhance long-term performance in industrial applications.
- The ideal moisture level (75–85%) ensured high microbial activity and efficient H_2S removal. Periodic nutrient injections prevented drying and maintained long-term performance. Moisture retention strategies (e.g., regulated flow of nutrient solution) can extend biofilter lifespan and stability.

- To achieve high H_2S removal efficiency, the biofilter must operate at an optimal ILR range where sufficient microbial activity is maintained, biofilter materials (PUF, CLC waste, biochar) do not become saturated too quickly, and mass transfer and adsorption are maximized. Based on the findings, the ideal ILR range is 500–1000 ppm at 0.5 L/min (ensures stability, high RE, and avoids microbial inhibition). While the critical ILR threshold is above 1500 ppm (causes performance drop due to saturation and microbial stress).
- Biofilter successfully reduced H_2S from 100–2000 ppm to below 100 ppm, depending on material selection and operational parameters. Saturation effects limited efficiency at high inlet H_2S concentrations, but optimization strategies improved performance. Based on the findings, lower initial H_2S (100–500 ppm) resulted in high removal efficiency (~90%), and moderate H_2S (500–1000 ppm) resulted in more stable RE (~80%). High H_2S (>1500 ppm) resulted in RE drop (65–70%) due to saturation.

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Author contributions

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There are no competing financial, professional, or personal interests from other parties.

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EKSPERIMENTINIS BIODUJŲ VALYMO NUO SIEROS VANDENILIO TYRIMAS, TAIKANT BIOFILTRĄ SU AKYTOJO BETONO ATLIEKŲ IR BIOANGLIES ĮKROVOMIS

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Santrauka

Šiame tyrime nagrinėjamas sieros vandenilio (H_2S) šalinimo iš biodujų efektyvumas, naudojant biofiltrą, užpildytą akytojo lengvojo betono atliekomis ir bioanglimi. Laboratorinis biofiltras buvo suprojektuotas ir išbandytas esant skirtingoms eksploatacinėms sąlygoms: keičiant pradinę H_2S koncentraciją (100–2000 ppm), dujų srautų greitį (0,2–1,0 L/min), temperatūrą (25–35 °C) ir drėgmę (70–90 %). Tyrimo rezultatai parodė, kad H_2S šalinimo efektyvumas siekė 95 % esant mažiems oro srautams ir esant nedidelėms pradinėms H_2S koncentracijoms. Palyginimui, kai dideli oro srautai – efektyvumas sumažėjo iki 88 %, o padidėjus H_2S koncentracijoms – efektyvumas sumažėjo iki 87 %. Aukštą biofiltro efektyvumą ir stabilumą lėmė bioanglies adsorbcinės savybės bei Fe_2CO_3 modifikuotų akytojo lengvojo betono atliekų katalizinė oksidacija. Tyrimo išvados leidžia teigti, kad hibridiniai biofiltrai, kuriuose naudojamos atliekų pagrindu gautos medžiagos, yra aplinkai tvari ir ekonomiškai efektyvi biodujų valymo alternatyva, palyginti su įprastais cheminiais ir fizikiniais metodais.

Reikšminiai žodžiai: sieros vandenilio šalinimas, biofiltras, bioanglis, akytojo betono atliekos, mikrobiologinė desulfurizacija, biodujų valymas.