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Optimization of Intermittent Spraying On-Time Duration in a Bioscrubber for Biogas Desulfurization at a Biogas Power Plant

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ABSTRACT
Hydrogen sulfide (H_2S) in biogas can corrode mechanical equipment and reduce generator reliability at biogas power plants (BPPs). Intermittent spraying has been reported to outperform continuous spraying in biological desulfurization, yet most studies varied the OFF-time while keeping the ON-time fixed. This study evaluated the effect of intermittent spraying ON-time on H_2S removal, CO_2 removal, and methane fraction in a bioscrubber (1,000 Nm^3/h) at a BPP in North Sumatra, Indonesia, using digester lagoon effluent as spraying liquid and a fixed 2-hour OFF-time. Five ON-time settings (5, 10, 20, 30, and 40 min; Treatments A–E) were run sequentially on a single day under constant operating conditions, with five repeated gas-analyzer readings per treatment, analyzed by one-way ANOVA and Tukey's HSD. H_2S removal rose from 91.45% to 94.61% with longer ON-time, but gains were small beyond 20 minutes. CO_2 removal (10.81%) and the increase in methane fraction (1.79 percentage points) peaked at 20 minutes. A 20-minute ON/2-hour OFF schedule is therefore suggested as a compromise for the tested conditions, with estimated circulated liquid volume and pumping energy 29–43% lower than at 30–40 minutes. Findings are preliminary because of the single-day design.

INTRODUCTION

Biogas produced through anaerobic digestion at biogas power plants (BPPs) primarily contains methane (CH_4) as the main energy carrier, carbon dioxide (CO_2), and several impurities such as hydrogen sulfide (H_2S), water vapor, and siloxanes (Nsair et al., 2020). Among these impurities, H_2S is the most critical because it is corrosive to metallic components in piping, compressors, and generator engines, and produces harmful SO_x emissions when combusted without prior treatment (Jmili et al., 2024). A special issue dedicated to advances in biogas desulfurization emphasizes that H_2S control is a prerequisite before biogas can be used as generator fuel or injected into a gas grid (Ramírez, 2020). A desulfurization step upstream of the generator is therefore generally required.

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Biogas desulfurization technologies are broadly grouped into physicochemical methods (e.g., activated-carbon adsorption, chemical absorption using alkaline or oxidant solutions) and biological methods (bioscrubbers, biotrickling filters, biofilters). Life-cycle assessments show that biological technologies, particularly anoxic biotrickling filtration, have a lower environmental impact than physicochemical methods when a nitrification facility is already available on-site (Cano et al., 2018). Recent comprehensive reviews further affirm that chemolithoautotrophic-based biological processes offer a more cost-effective and sustainable approach (Cattaneo et al., 2023; Dada et al., 2025). Nevertheless, field-scale bioscrubber implementation does not always proceed optimally; an evaluation of U.S. dairy farms, for instance, found that scrubber performance was often constrained by the lack of dedicated operators to routinely monitor the system (Choudhury et al., 2019), indicating that simple, resource-efficient operating designs are a practical necessity rather than merely a technical-efficiency concern.

In biological desulfurization units, H_2S is removed by absorption into a sprayed liquid phase, followed by biological oxidation by sulfur-oxidizing bacteria attached to the packing media, such as the genus *Acidithiobacillus*. Terminology differs among studies: packed-bed systems with recirculated liquid are often called biotrickling filters in the literature, whereas the term bioscrubber is used at the study site and in this paper for the unit described in the Methods. Sulfur-oxidizing bacteria of this genus are acidophilic and typically perform best at about pH 1–2, so changes in the recirculating liquid's pH can affect the stability of the microbial community and removal performance (Mora et al., 2019). Numerous bioscrubber configurations have been developed and tested, ranging from fully aerobic systems that remain stable even during short-term shutdowns (San-Valero et al., 2019), anoxic systems fed with nitrate-rich effluent to drive simultaneous denitrification (Cano et al., 2021; Tilahun & Çalli, 2024), continuous stirred-tank reactors for elemental sulfur production (González-Cortés et al., 2021), to sunlight-driven alkaline bioscrubbers coupled with microalgae (Gonzalez-Sanchez et al., 2026) and two-stage systems for sulfur valorization (Guimerà et al., 2020). Application scales likewise range from laboratory units (Zhuo et al., 2019; Bravo et al., 2018) to pilot- and full-scale installations at landfill sites (Torres-Herrera et al., 2024, 2025; Severi et al., 2024; Brito et al., 2025) and livestock farms (Liu et al., 2019). In Indonesia, preliminary microbial desulfurization studies using bioscrubbers have also been reported (Prasetyo et al., 2020), yet operational studies at commercial BPP industrial scale remain limited.

One key finding in the biotrickling filter literature is the superiority of intermittent over continuous spraying. A full-scale study by Bu et al. (2021) demonstrated an increase in H_2S removal efficiency from 36.3% under continuous mode to 99.59% under intermittent mode, with a 10-minute spraying interval per 2 hours proving the most effective and saving up to 83% in energy compared with continuous operation—although the same study also identified a transient H_2S breakthrough phenomenon during the pump-on period. Similar findings were reported for a full-scale biotrickling filter tested with different nitrate sources, where intermittent spraying remained superior regardless of the water type used—whether effluent or synthetic solution (Piovezan et al., 2024), a finding directly relevant to this study, which uses digester effluent overflow water as the spraying source. The superiority of intermittent operation is further supported by controlled micro-aeration principles, in which periodic oxygen supply sustains sulfur-oxidizing bacterial activity without disturbing the anaerobic digestion process itself (Rajagopal & Goyette, 2024; Di Costanzo et al.,

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2024). Beyond spraying duration, recirculating liquid flow rate also affects removal performance, as shown in a power-to-X electroscrubbing system that achieved near-100% H_2S removal (Borgquist et al., 2023), and in a study on the impact of anoxic desulfurization on the methane content of treated biogas (Quijano et al., 2021).

Nonetheless, the study by Bu et al. (2021) focused on varying the off-time interval (every 2, 8, and 24 hours) while keeping the on-time duration fixed at 10 minutes, leaving unanswered whether 10 minutes is in fact the optimal on-time duration, or whether shorter or longer durations could yield equal or better results. The transient breakthrough phenomenon that occurs during the spraying period has also rarely been examined specifically through on-time duration variation. In addition, mathematical models of biological desulfurization remain largely empirical and depend on experimental data on operating-duration variation that remains scarce (Cattaneo et al., 2023; Wang et al., 2024). This study addresses this gap by varying the ON-time duration (5, 10, 20, 30, and 40 minutes) at a fixed 2-hour OFF-time—a duration chosen because it has been shown to sustain excellent H_2S removal performance at low H_2S concentrations (<100 ppmv), and because it is also the settling time required for the digester lagoon effluent overflow water to become sufficiently clear before being sprayed into the bioscrubber.

This study was conducted at a biogas power plant in North Sumatra, Indonesia, that operates a closed-loop bioscrubber fed with recirculating liquid sourced from the digester lagoon effluent overflow. To date, spraying has been performed once every 2 hours until the water level inside the bioscrubber reaches half of its full capacity, without an in-depth study of the optimal ON-time duration. The objectives of this study were (1) to evaluate the effect of intermittent spraying ON-time duration on H_2S removal efficiency, CO_2 removal, and the increase in methane fraction [$CH_4/(CH_4 + CO_2)$] in an industrial-scale bioscrubber; and (2) to identify the ON-time duration that gives the best compromise among H_2S removal, CO_2 removal and methane fraction, and the estimated circulated liquid volume and pumping energy. Unlike previous studies that varied the OFF-time interval, this study isolates the ON-time duration while holding the OFF-time constant.

METHODS

1. Study Site and Object

This study was conducted at a biogas power plant in North Sumatra, Indonesia (the plant is not named at the company's request). The plant processes biogas generated through anaerobic digestion in a covered-lagoon digester. The desulfurization unit under study is a bioscrubber operated in closed-loop mode: raw biogas flows through a packing medium wetted by a liquid sprayed periodically from the top of the column (top-spray configuration), and the liquid is recirculated within the same column. The term bioscrubber is retained because it is the name used for this unit at the plant; part of the literature cited here calls comparable packed-bed systems biotrickling filters. The liquid used for spraying is neither clean water nor a synthetic nutrient solution, but rather effluent overflow water from the biogas lagoon digester, consistent with the effluent-as-nutrient-source approach shown to be effective in biotrickling filters in previous studies (Piovezan et al., 2024; Cano et al., 2021).

The bioscrubber is rated at a capacity of 1,000 Nm^3/h at an atmospheric design pressure and a design temperature of 60 °C, with actual operating conditions of about 0 barg and 35–40 °C. The

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recirculating spray liquid is driven by a centrifugal pump rated at 30 m^3/h, with a minimum suction pressure of 0 barg and a discharge pressure of 3.6 barg. Under the plant's standard operating procedure (SOP), the water in the bioscrubber is changed every 2 hours (the OFF-time). The liquid level is read on a sight glass graduated from 0 to 20: during the 2-hour OFF-time the level falls to about 5–6, and during the ON-time (water change and spraying circulation) it is refilled to a level of 10–17, never to full. A small amount of oxygen is supplied to the bioscrubber through a valve (micro-aeration); the oxygen supply rate was not measured. The pump capacity was used as the basis for estimating the circulated liquid volume and pumping energy associated with each treatment (see Section 2).

2. Experimental Design

The study used a single-factor experimental design with five treatment levels, namely intermittent spraying ON-time duration: 5 minutes (Treatment A), 10 minutes (Treatment B), 20 minutes (Treatment C), 30 minutes (Treatment D), and 40 minutes (Treatment E). The OFF-time interval between spraying events was held constant at 2 hours across all treatments (Table 2, Figure 1). The 2-hour OFF-time was chosen for two reasons: (1) it follows the company's SOP, which sets the spraying interval at every 2 hours, and (2) this duration allows suspended solids carried by the digester lagoon effluent overflow water to settle naturally, so that the water sprayed into the bioscrubber is relatively clear and unlikely to clog the nozzles or packing media. By holding the OFF-time constant, the ON-time duration could be isolated, allowing its direct effect on desulfurization performance to be identified with greater precision (Bu et al., 2021). The design's midpoint (10 minutes) refers to the duration previously shown to be effective and robust in a benchmark study (Bu et al., 2021), while 5 minutes tests the lower bound for potential water and energy conservation and mitigation of transient breakthrough, and 20, 30, and 40 minutes test the upper bound to evaluate the potential added benefit of flushing by-products (sulfur, excess biomass) against the risk of biofilm disturbance and reduced gas contact time.

Table 2. Design of Intermittent Spraying ON-Time Treatments and Estimated Resource Consumption

Treatment	On-time (min)	Off-time (h)	Readings (n)	Duty cycle (%)	Est. circulated volume/ event (m^3)	Est. circulated volume/day (m^3)	Est. pumping energy/day (kWh)
A	5	2	5	4.00	2.5	28.8	4.4
B	10	2	5	7.69	5.0	55.4	8.5
C	20	2	5	14.29	10.0	102.9	15.8
D	30	2	5	20.00	15.0	144.0	22.2
E	40	2	5	25.00	20.0	180.0	27.7

The circulated liquid volume and pumping-energy estimates in Table 2 were calculated from the installed circulation pump capacity (Q = 30 m^3/h) and an assumed pump-motor efficiency (η) of 65% (a typical value for small-to-medium centrifugal pumps). Daily circulated volume was calculated as $Q \times t_{ON}/(t_{ON} + t_{OFF}) \times 24$ h, and pumping energy as $\rho g H Q t/\eta$, with a head (H) equivalent to the 3.6 barg discharge pressure (≈ 36.7 m of water column). These are theoretical

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estimates, not measurements: they refer to the volume pumped through the closed loop rather than fresh-water make-up, and they are not measured electrical power. They serve only as a relative indicator of resource use across treatments.

3. Measurement Procedure

All five treatments were run in sequence (A, B, C, D, E) on a single day, so that day-to-day variation in feed biogas, temperature, microbial activity, and liquid quality could not act as an additional variable. Biogas flow rate, temperature, pressure, bioscrubber condition, and packing condition followed the plant SOP and were kept the same throughout the day. For each treatment, the liquid level was first set to the SOP level (10–17 on the sight glass); after about 5 minutes the ON-time was started and timed, and after the ON-time ended the gas composition was measured with five readings at each of two sampling points: (1) the bioscrubber inlet (before contact with the sprayed liquid) and (2) the bioscrubber outlet (after the spraying process), using a portable gas analyzer measuring CH_4 (%), H_2S (ppm), CO_2 (%), and O_2 (%) concentrations, as well as column operating pressure and temperature (°C). The five readings of each treatment are repeated instrument readings within one operating run (n = 5 per treatment), not independent replicates on separate days; their mean ± standard deviation is reported. Inlet O_2 was below the analyzer's detection limit and is reported as 0.00%, consistent with the anaerobic origin of the biogas. The pH and dissolved oxygen (DO) of the recirculating liquid inside the bioscrubber could not be measured in this study because the system is fully enclosed; opening the circulation line to install in-line sensors would risk disrupting the plant's continuous operation and potentially causing biogas leakage.

4. Data Analysis

Mean ± standard deviation (SD) of the five readings was calculated for each treatment. H_2S and CO_2 removal efficiencies were calculated with Equation (1), the same formula used for routine performance calculation at the plant,

$$\text{Removal efficiency (\%)} = \frac{(C_{\text{in}} - C_{\text{out}})}{C_{\text{in}}} \times 100 \quad (1)$$

where C_{in} and C_{out} are the concentrations at the bioscrubber inlet and outlet, respectively. To evaluate the change in biogas quality, the methane fraction (MF) was calculated at the inlet and the outlet as the share of CH_4 in the sum of CH_4 and CO_2 (Equation 2), and the increase in methane fraction was calculated as the outlet value minus the inlet value, in percentage points (Equation 3).

$$\text{MF (\%)} = \frac{CH_4}{CH_4 + CO_2} \times 100 \quad (2)$$

$$\text{Increase in methane fraction (pct. points)} = MF_{\text{out}} - MF_{\text{in}} \quad (3)$$

MF excludes O_2, N_2, and other gases, so it is not the simple CH_4/CO_2 ratio. Differences among treatments were tested using one-way analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$ (n = 5 readings per treatment, N = 25), followed by Tukey's Honestly Significant Difference (HSD) post-hoc test to identify which treatment pairs differed. Homogeneity of the inlet composition among treatments was examined with the same ANOVA applied to the inlet values. ANOVA assumptions were checked for each response variable: residual normality with the Shapiro–Wilk test ($p = 0.64$–0.77 for H_2S removal, CO_2 removal, and the increase in methane fraction), homogeneity of

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Knowledge & Innovation in Molecular and Industrial Applications (KIMIA)
Vol. 01, No. 1, June 2026

variance with Levene's test (median-centered; p = 0.24–0.89), and outliers as standardized residuals (all within ±3). The Kruskal–Wallis test gave the same conclusions (p < 0.001 for all three variables). Because all treatments were run on the same day, day was not included as a blocking factor; however, the five readings are repeated readings within one run, so the p-values describe differences among treatments in this run and do not demonstrate day-to-day reproducibility. All statistical analyses were performed in Python 3 using the SciPy and statsmodels libraries.

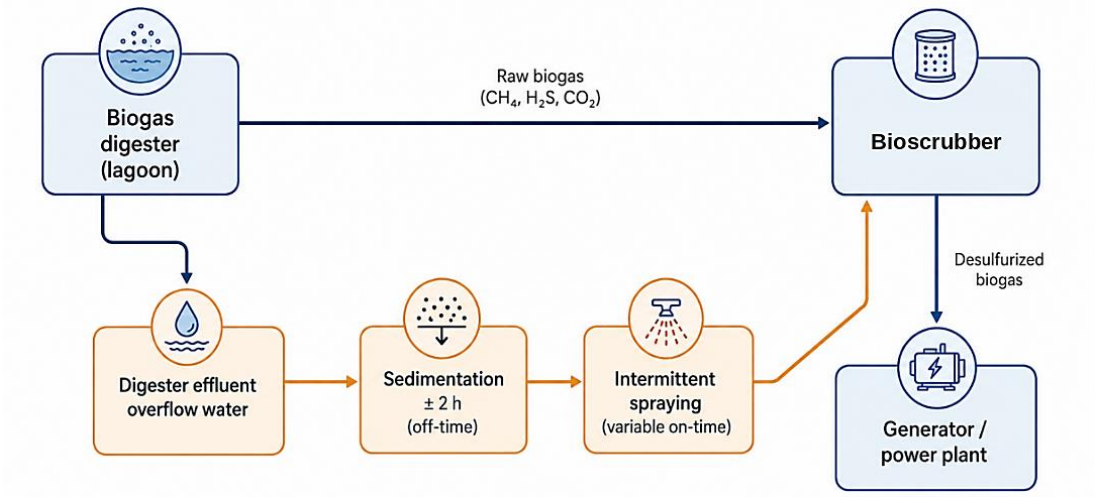


Figure 1. Process Flow Schematic of Intermittent Bioscrubber Operation at the Biogas Power Plant

RESULTS

1. Biogas Composition Before and After the Bioscrubber

Table 3 presents the mean ± standard deviation of biogas quality parameters before and after the bioscrubber for the five treatments. Inlet H_2S concentrations were similar across treatments, ranging from 1,506.4 to 1,529.8 ppm. One-way ANOVA on the inlet values showed no significant difference in inlet H_2S ($F(4,20) = 0.30$; $p = 0.875$), CH_4 ($F = 1.75$; $p = 0.179$), or CO_2 ($F = 0.84$; $p = 0.519$), so differences in outlet performance are less likely to reflect variation in feed quality within this run (Table 3, Figure 2). Outlet H_2S concentration decreased consistently with increasing ON-time duration, from 128.8 ppm (Treatment A) to 82.2 ppm (Treatment E).

Table 3. Descriptive Statistics (Mean ± SD, n = 5 Readings) of Biogas Composition Before and After the Bioscrubber for Each ON-Time Treatment

Treatment	Inlet CH_4 (%)	Inlet H_2S (ppm)	Inlet CO_2 (%)	Inlet O_2 (%)	Outlet CH_4 (%)	Outlet H_2S (ppm)	Outlet CO_2 (%)	Outlet O_2 (%)
A	61.56±0.24	1,506.4±45.1	35.66±0.24	0.00	57.76±0.24	128.8±4.3	32.80±0.16	1.78±0.04
B	61.70±0.22	1,519.6±44.8	35.84±0.21	0.00	58.06±0.24	121.2±3.5	32.66±0.15	1.82±0.04
C	61.94±0.21	1,517.0±29.8	35.90±0.16	0.00	59.72±0.26	90.6±2.7	32.02±0.08	1.82±0.04
D	61.68±0.26	1,529.8±35.3	35.78±0.28	0.00	59.10±0.16	87.6±2.1	32.84±0.11	1.82±0.04
E	61.76±0.24	1,526.6±28.5	35.86±0.24	0.00	58.50±0.16	82.2±1.9	33.04±0.11	1.82±0.04

Note: Inlet O_2 was below the detection limit of the gas analyzer and is reported as 0.00%.

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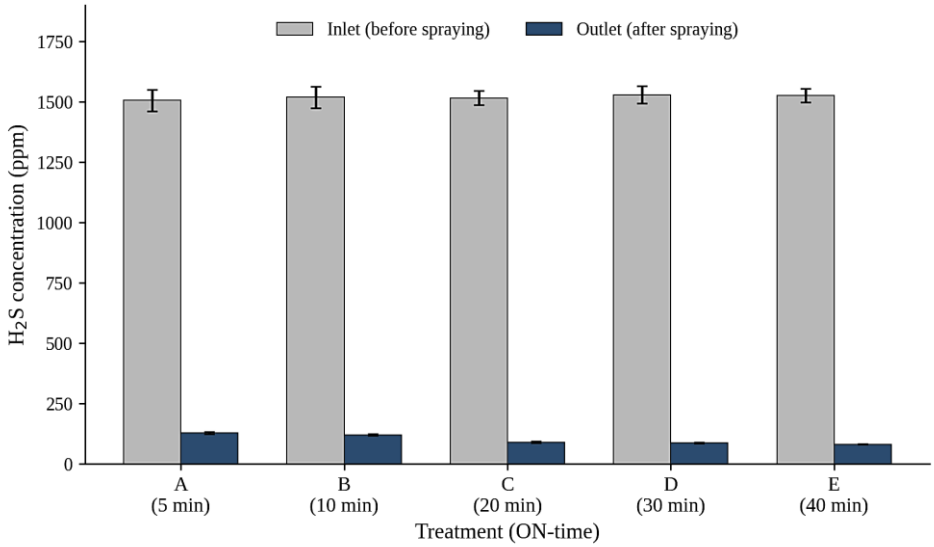


Figure 2. Biogas H_2S Concentration Before and After the Bioscrubber for Each ON-Time Treatment

Outlet CH_4 concentration was lower than inlet CH_4 in all treatments (Table 3), even though CO_2 and H_2S were removed. Outlet gas contained 1.78–1.82% O_2, whereas inlet O_2 was below the detection limit. Because a small amount of oxygen is supplied deliberately to the bioscrubber through a valve (micro-aeration; Rajagopal & Goyette, 2024; Di Costanzo et al., 2024), the lower outlet CH_4 is consistent with dilution by the supplied air; N_2 was not measured, which limits this interpretation. Partial methane oxidation, reported for anoxic desulfurization (Quijano et al., 2021), cannot be excluded but was not examined here. Column pressure was read with a low-range pressure gauge and was the same in all treatments. The readings were slightly negative (−1 mbar at the inlet and −20 mbar at the outlet), i.e., below atmospheric pressure, because the outlet gas is drawn by a compressor toward the next unit and the inlet–outlet difference reflects the pressure drop across the packing. These readings are therefore compatible with the nominal operating pressure of about 0 barg (−20 mbar ≈ −0.02 barg) given in the Methods. Outlet temperature ranged from 33 to 35 °C (mean 34.4 ± 0.55 °C), slightly below the nominal operating range (35–40 °C), with no practically meaningful difference among treatments, suggesting that temperature was not a major source of variation among treatments.

2. H_2S Removal Efficiency

One-way ANOVA indicated a significant difference in H_2S removal efficiency among treatments ($F(4,20) = 204.80$; $p < 0.001$). Efficiency increased monotonically from 91.45 ± 0.19% (Treatment A) through 92.02 ± 0.14, 94.02 ± 0.29, and 94.27 ± 0.24% to 94.61 ± 0.22% (Treatment E) (Figure 3). Tukey's HSD post hoc test showed that all treatment pairs differed significantly ($p < 0.05$) except C–D ($p = 0.435$) and D–E ($p = 0.152$) (Table 5), indicating that the rate of improvement flattened sharply beyond 20 minutes. Marginal-gain analysis (Table 4) confirms this pattern: the efficiency gain per additional minute of spraying was 0.115 percentage points/min over the 5–10-minute range, rose to 0.200 percentage points/min (the largest gain) over the 10–20-minute range,

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Knowledge & Innovation in Molecular and Industrial Applications (KIMIA)
Vol. 01, No. 1, June 2026

but dropped sharply to only 0.025 and 0.034 percentage points/min over the 20–30- and 30–40-minute ranges, respectively.

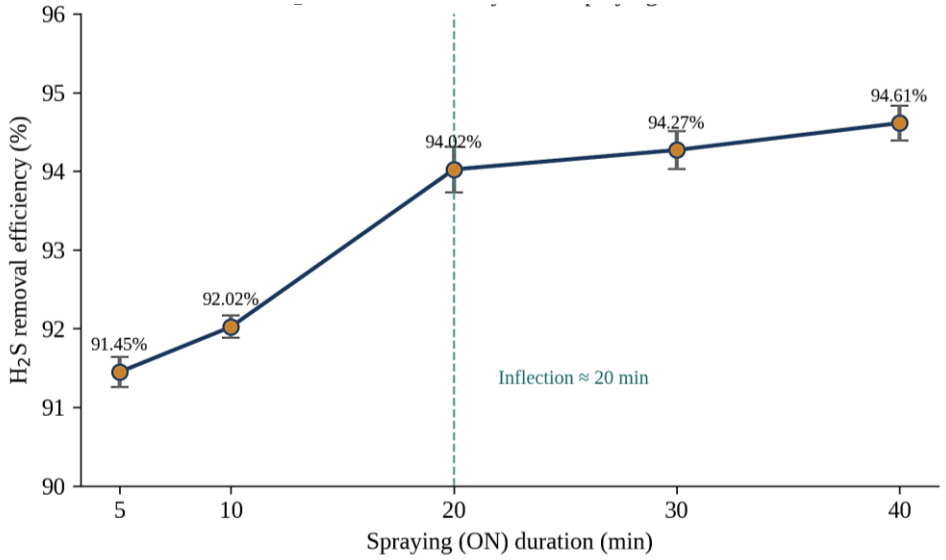


Figure 3. H_2S Removal Efficiency Versus Spraying ON-Time Duration

Table 4. Marginal-Gain Analysis of H_2S Removal Efficiency Between Consecutive Treatments

Treatment transition	Δ on-time (min)	Δ H_2S efficiency (pct. points)	Gain per minute (pct. pts/min)
A → B	5 → 10	0.57	0.115
B → C	10 → 20	2.00	0.200
C → D	20 → 30	0.25	0.025
D → E	30 → 40	0.34	0.034

3. CO_2 Removal and Increase in Methane Fraction

Unlike the monotonic pattern observed for H_2S, CO_2 removal and the increase in methane fraction showed a non-monotonic pattern, peaking at Treatment C (20 minutes) (Figure 4). One-way ANOVA indicated significant differences in CO_2 removal ($F(4,20) = 44.00$; $p < 0.001$) and in the increase in methane fraction ($F(4,20) = 154.11$; $p < 0.001$). Tukey's HSD showed that Treatment C was significantly higher than all other treatments for both parameters ($p < 0.05$ for all pairs involving C). Among Treatments A, B, D, and E, CO_2 removal differed significantly only for the pairs A–B and B–E; the pairs A–D, A–E, B–D, and D–E were not significantly different (Table 5). For the increase in methane fraction, only the pair B–E was not significant ($p = 0.441$). The highest mean CO_2 removal was recorded at Treatment C, at 10.81 ± 0.56%, compared with 8.02 ± 0.39, 8.87 ± 0.20, 8.21 ± 0.49, and 7.86 ± 0.31% for Treatments A, B, D, and E. Similarly, the highest increase in methane fraction occurred at Treatment C, at 1.79 ± 0.15 percentage points—about 1.8 to 3.9 times higher than the other treatments (0.46 ± 0.10, 0.74 ± 0.06, 0.99 ± 0.07, and 0.64 ± 0.05 percentage points for A, B, D, and E).

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Vol. 01, No. 1, June 2026

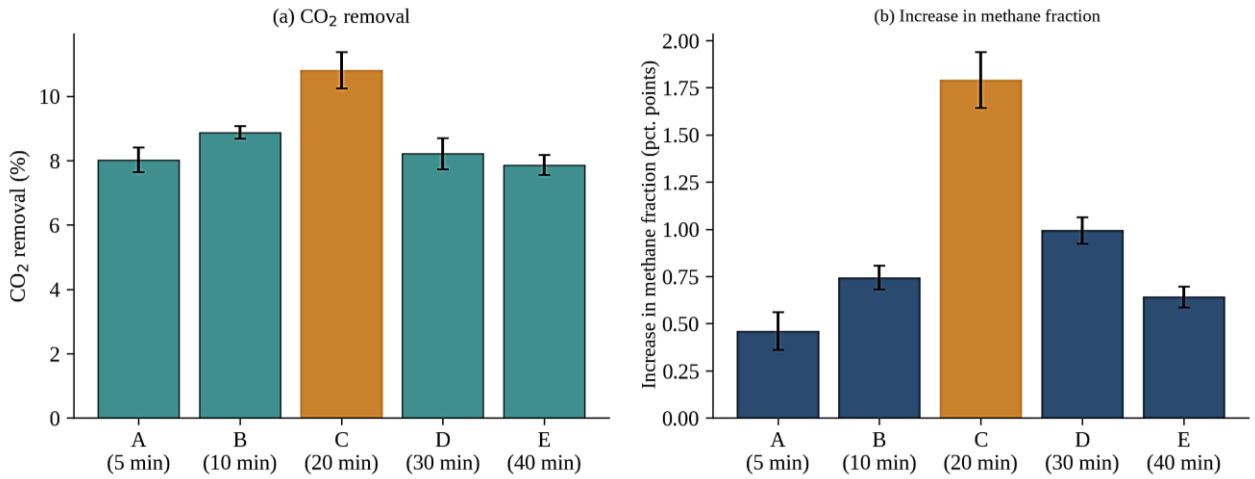


Figure 4. (a) CO_2 removal; (b) increase in methane fraction, for each ON-time treatment

Table 5. Summary of One-Way ANOVA and Tukey HSD Post-Hoc Results (α = 0.05) Among ON-Time Treatments

Response parameter	F(4,20)	p-value	Non-significant (ns) treatment pairs
H_2S removal efficiency (%)	204.80	<0.001	C–D (p = 0.435); D–E (p = 0.152); all other pairs significant
CO_2 removal (%)	44.00	<0.001	A–D; A–E; B–D; D–E; all other pairs significant (incl. A–B, B–E)
Increase in methane fraction (pct. points)	154.11	<0.001	B–E (p = 0.441); all other pairs significant

4. Estimated Circulated Liquid Volume and Pumping Energy

Based on the installed circulation pump capacity (30 m^3/h), the estimated daily circulated liquid volume and pumping energy increase proportionally with longer ON-time durations (Table 2). Treatment E was estimated to circulate ≈180.0 m^3 of liquid/day and to use ≈27.7 kWh of pumping energy/day, compared with only ≈102.9 m^3/day and ≈15.8 kWh/day for Treatment C—an estimated reduction of ≈77.1 m^3 (42.9%) and ≈11.9 kWh (42.9%) per day if Treatment C were adopted in place of Treatment E. Compared with Treatment D (≈144.0 m^3/day; ≈22.2 kWh/day), Treatment C would reduce the estimate by ≈41.1 m^3 (28.6%) and ≈6.3 kWh (28.6%) per day. These are theoretical values derived from the pump rating and an assumed efficiency, not measured field consumption, and because the liquid is recirculated they describe pumped volume rather than fresh-water use. In exchange, H_2S removal efficiency was only 0.59 percentage points lower than at Treatment E (94.02% vs. 94.61%), while CO_2 removal and the increase in methane fraction were higher than at Treatment D or E.

DISCUSSION

Within the tested range of ON-time durations, the bioscrubber achieved 91–95% H_2S removal at an inlet load of about 1,500 ppm. Previous studies report that intermittent spraying outperforms

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continuous spraying (Bu et al., 2021; San-Valero et al., 2019); however, no continuous-spraying control was included here, so the present data cannot show that intermittent spraying is superior to continuous spraying. The response pattern observed in this study—H_2S removal efficiency increasing monotonically with longer ON-time, while CO_2 removal and the increase in methane fraction instead peaked at an intermediate duration (20 minutes) before declining—has not been widely reported in previous literature, which generally focused on varying the off-time interval at a fixed on-time (Bu et al., 2021; Piovezan et al., 2024). Because pH, DO, alkalinity, liquid flow rate, gas flow rate, pressure drop, and liquid-phase sulfur species were not measured, the mechanisms discussed below are hypotheses rather than confirmed explanations.

The monotonic H_2S pattern is consistent with biological oxidation by sulfur-oxidizing bacteria, which requires adequate gas–biofilm contact for the enzymatic reactions to proceed (González-Cortés et al., 2021; Cattaneo et al., 2023). Longer spraying durations may deliver a greater volume of fresh liquid to wet the biofilm, renewing the thin liquid film that mediates H_2S diffusion toward bacterial cells while also supplying nutrients and possibly stabilizing the pH of the biofilm's microenvironment (Mora et al., 2019). The sharply flattening rate of improvement beyond 20 minutes (Table 4) suggests that the marginal benefit of additional wetting diminishes, possibly because the H_2S oxidation rate approaches the bacteria's maximum kinetic limit (zero-order/saturation kinetics) at the relatively constant feed H_2S load (~1,500 ppm) examined in this study—considerably higher than the low concentrations examined in several previous modeling studies (Zhuo et al., 2019; Wang et al., 2024).

In contrast, CO_2 removal may be more strongly governed by physical absorption, which depends on the gas–liquid interfacial contact area and the alkalinity capacity of the recirculating liquid (Guimerà et al., 2020; Wang et al., 2024). At short spraying durations (5–10 minutes), limited contact time could constrain CO_2 mass transfer into the liquid phase. At 20 minutes, gas–liquid contact and fresh-liquid availability may reach a balance that supports the highest CO_2 absorption observed. At longer durations (30–40 minutes), CO_2 removal decreased, possibly due to partial flooding of the packing media from excess wetting, which reduces the effective gas–liquid surface area (channeling), or to reduced gas retention time as the flow pattern shifts with a larger recirculating liquid volume (Borgquist et al., 2023; Quijano et al., 2021). This pattern may also indicate that excessive spraying disturbs biofilm stability and reduces the effective gas–media contact time, as hinted at in earlier work on trickling strategies (Bu et al., 2021). None of these explanations could be tested with the data collected.

Treatment C (20-minute ON/2-hour OFF) was selected as the best compromise among H_2S removal, CO_2 removal and methane fraction, and the estimated circulated liquid volume and pumping energy. Although Treatment E produced the highest H_2S removal efficiency (94.61%), the difference from Treatment C (94.02%) was only 0.59 percentage points—statistically detectable but practically small (Table 5)—while Treatment E was estimated to circulate about 1.75 times the liquid volume and use about 1.75 times the pumping energy of Treatment C (≈180.0 vs. ≈102.9 m^3/day; ≈27.7 vs. ≈15.8 kWh/day), and it gave lower CO_2 removal and a smaller increase in methane fraction. Beyond 20 minutes, the marginal H_2S gain fell to 0.025–0.034 percentage points/min (Table 4). These findings are practically relevant for the study site, since the plant's previous practice—spraying until the water level reaches half of the bioscrubber's full capacity without an explicit duration limit—

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may be inconsistent across operating periods and is not optimized for outlet gas quality or resource use. A fixed 20-minute ON/2-hour OFF schedule could deliver consistent performance with an estimated 29–43% lower circulated volume and pumping energy than 30–40 minutes. This recommendation applies to the conditions tested (one plant, one range of inlet H_2S load, a single-day run) and should be confirmed by repeating the experiment on different days.

Many BPPs use ordinary water as the process liquid; the plant studied uses digester effluent overflow to make use of a waste stream and to reduce operating cost. Using digester lagoon effluent overflow water as the spraying liquid—rather than clean water or a synthetic nutrient solution—is supported as remaining effective for H_2S removal regardless of the water source (Piovezan et al., 2024; Cano et al., 2021), while also representing a value-added use of a side stream that supports the BPP's operational sustainability. Techno-economic assessments of other desulfurization systems likewise indicate that optimizing operating parameters—including duration and flow rate—contributes to long-term operating cost savings (Resnikow et al., 2025; Castagnoli et al., 2025).

This study has several limitations. First, all treatments were run sequentially (A to E, not randomized) on a single day, and each treatment was represented by five repeated readings rather than independent replicates on different days. Treatment order and time of day are therefore confounded with ON-time, and the ANOVA p-values cannot show reproducibility across days; the results should be regarded as preliminary. Second, no continuous-spraying control was included. Third, the pH and DO of the recirculating liquid inside the bioscrubber could not be measured because the system is fully enclosed, so mechanistic interpretation of the biofilm microenvironment—particularly to explain the non-monotonic CO_2 removal pattern—remains inferential and requires confirmation through in-line pH/DO sensors in future facility designs, consistent with the data gap on oxygen-limited conditions highlighted in recent reviews (Cattaneo et al., 2023). Fourth, the circulated liquid volume and pumping energy are theoretical estimates, not measurements. Fifth, this study tested only a single range of feed H_2S load (±1,500 ppm), so generalizing the 20-minute duration to substantially different H_2S loads requires further validation, ideally through predictive modeling approaches such as artificial neural networks (Clifford et al., 2025), surrogate models (Yang et al., 2025), response surface methodology (Mugagga et al., 2022), or digital twins (Pallavicini et al., 2023) that enable continuous optimization based on real operating data. Sixth, other bioscrubber configurations, such as fully aerobic systems (San-Valero et al., 2019), microalgae-based alkaline systems (Gonzalez-Sanchez et al., 2026), or moving-bed biofilm designs for impurities other than H_2S (Morral et al., 2022), were not directly compared in this study and represent promising directions for future research.

CONCLUSIONS

This study evaluated the effect of intermittent spraying ON-time duration (5, 10, 20, 30, and 40 minutes) at a fixed 2-hour OFF-time on the performance of a bioscrubber for biogas desulfurization at a commercial BPP in North Sumatra, Indonesia. In this single-day run, H_2S removal efficiency increased from 91.45% to 94.61% with longer ON-time ($p < 0.001$), though the rate of improvement flattened sharply beyond 20 minutes. In contrast, CO_2 removal and the increase in methane fraction peaked at the 20-minute ON-time (Treatment C), at 10.81% and 1.79 percentage points respectively, before declining at longer durations. Considering H_2S removal, CO_2 removal

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and methane fraction, and the estimated circulated liquid volume and pumping energy (estimated to be 29–43% lower than at 30–40 minutes; theoretical values), a 20-minute ON/2-hour OFF schedule is suggested for this bioscrubber under the tested conditions, replacing the plant's previous practice of spraying until the water level reached half of the bioscrubber's capacity without an optimized duration basis. Future research should repeat the experiment on different days with randomized treatment order, include a continuous-spraying control, install in-line pH and DO sensors to confirm the microbiological mechanisms behind the non-monotonic CO_2 removal pattern, validate the optimal duration across a wider range of H_2S loads, and integrate predictive modeling approaches to support continuous operational optimization at other BPPs with similar characteristics.

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