Effect of pH on the performance of an acidic biotrickling filter for simultaneous removal of H₂S and siloxane from biogas

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ABSTRACT

Acidic biotrickling filters (BTF) can be used for simultaneous removal of hydrogen sulfide (H₂S) and siloxane from biogas. In this study, the performance of a BTF under different acidic pH conditions was investigated. The removal profile of H₂S showed that 90% of H₂S removal was achieved during the first 0.4 m of BTF height with down-flow biogas. Decamethylcyclopentasiloxane (D₅) removal decreased from 34.5% to 15.6% when the pH increased from 0.88 to 3.98. Furthermore, the high partition coefficient of D₅ obtained in under higher pH condition was attributed to the higher total ionic strength resulting from the addition of sodium hydroxide solution and mineral medium. The linear increase in D₅ removal with the mass transfer coefficient (k_L) indicated that the acidic recycling liquid accelerated the mass transfer of D₅ in the BTF. Therefore, the lower partition coefficient and higher k_L under acidic pH conditions lead to the efficient removal of D₅. However, the highly acidic pH blocked mass transfer of H₂S and O₂ gases to the recycling liquid. Low sulfur oxidation activity and low Acidithiobacillus sp. content also deteriorated the biodegradation of H₂S. Operating the BTF at pH 1.2 was optimal for simultaneously removing H₂S and siloxane.

Key words | biogas, biotrickling filter, hydrogen sulfide, pH, siloxane

HIGHLIGHTS

- Effect of pH on the performance of acidic BTF for simultaneous removal of H₂S and siloxane was investigated.
- A linear positive correlation was observed between the mass transfer coefficient and the removal efficiency of D₅.
- Evolution in microbial community under various acidic pH conditions was investigated.
- Operating the BTF at pH 1.2 was optimal for simultaneous efficient removal of H₂S and siloxane from biogas.

INTRODUCTION

Biogas from anaerobic digestion of organic compounds is a promising renewable biofuel that can be used to produce heat, steam, electricity, fuel, or for gas-grid injection (Chen et al. 2015). Apart from methane (CH₄) and carbon dioxide (CO₂), biogas contains trace impurities, such as hydrogen sulfide (H₂S) (50–10,000 ppmv) (Pipatmanomai et al. 2009) and siloxanes (10–400 mg/m³) (Dewil et al. 2006; Oshita et al. 2010; Raich-Montiu et al. 2014; Zhang et al. 2020). During biogas combustion, H₂S can corrode engines and metal piping and emit sulfur dioxide (SO₂) (Pipatmanomai et al. 2009).
developing an integrated biogas purification technology is crucial for increasing the benefits available by combining 
H2S and siloxanes abatement technologies. In our previous study, the feasibility of simultaneous removal of 
H2S and siloxanes directly from biogas was demonstrated using an acidic biotrickling filter (BTF) (Zhang et al. 2020). Unlike 
neutral BTFs inoculated with *Phyllobacterium myrsinae* (Wang et al. 2014), *Pseudomonas* sp. (Li et al. 2014; 
Santos-Clotats et al. 2019), and *Methyllobium* sp. (Boada et al. 2020) for biodegrading siloxanes, the degradation of decamethylcyclopentasiloxane (D5) is attributed to hydrolisis promoted by the acidic recycling liquid that results from the biodegradation of H2S by *Acidithiobacillus* sp. in the acidic BTF (Zhang et al. 2020). Cyclic D5 undergoes ring-opening hydrolisis to form linear oligomeric hexamethyltrisiloxane-1,5-diol and tetramethyldisiloxane-1,3-diol and is finally hydrolyzed to dimethylsilanediol. This is a similar degradation pathway to that of octamethycyclotetrasiloxane (D4) in soil (Xu 1999). Therefore, in aquatic environments and especially under extremely acidic conditions, hydrolisis is considered one of the major degragation pathways of siloxanes.

Furthermore, hydrolisis of polydimethylsiloxane fluids is much faster at pH 2–4 than at pH 6 (Ducom et al. 2013). Siloxanes hydrolisis further promotes their mass transfer from biogas to the BTF recycling liquid, implying that operating BTFs at lower pH values should improve siloxanes abatement. Moreover, acidic BTFs were found to lead to specialization of the bacterial community and the prevalence of *Acidithiobacillus* sp. (Montebello et al. 2013; Arespacochaga et al. 2014a; Tu et al. 2016). However, an extremely acidic pH would deteriorate H2S biodegradation because high SO42− concentrations at low pH are toxic to microorganisms (Jin et al. 2005). Furthermore, faster growing *Ferroplasma acidiphilum* displaces *Acidithiobacillus* sp. in highly acidic environments (Zhang et al. 2020). In this case, the H2S is degraded to sulfur, which clogs the packing layer of the BTF. Correspondingly, the gas–liquid mass transfer of siloxanes is blocked, leading to deterioration of their abatement. Therefore, pH is a key parameter that directly effects the operational performance of a BTF, especially for achieving effective removal of H2S and siloxanes simultaneously.

In this study, biogas from anaerobic digestion of sewage sludge was used as the gas feedstock of an acidic BTF to investigate the performance of BTF under five acidic pH conditions. A gas–liquid partition test was also carried out to evaluate the mass transfer coefficients of D5. Furthermore, the microbial community in the BTF under various acidic pH conditions was analyzed and compared to explain the changing performances of the BTF.

MATERIALS AND METHODS

BTF setup and operating conditions

The study was carried out on-site using an experimental BTF that was installed at a wastewater treatment plant with a sewage-treatment capacity of 847,000 m3/day, located in Kyoto, Japan. Biogas from a thermophilic anaerobic digestion tank of thickened primary sludge (maintained at 55°C for 10 days) was fed to the BTF. The biogas production reached 1,200 Nm3/h, and contained H2S (600–1,100 ppmv), D5 (15.5–52.8 mg/m3), and D4 (2.5–12.3 mg/m3). The experimental apparatus (Zhang et al. 2020) was a polyvinyl chloride column with a 15 cm inner diameter was filled with commercial polypropylene carrier (KG-088-O15; Kan-saiKako Co., Osaka, Japan) and packed to a height of 1.0 m. The length, particle diameter, and specific surface area of polypropylene carrier were 15 mm, 15 mm, and 960 m2/m3, respectively. The inner temperature of the column was maintained at 30°C using a water heating system.

According to Tu et al. (2016), inoculation with *Acidithiobacillus* sp. is an ideal way to reduce the acclimation times of a BTF with a high H2S-degrading capability. Therefore, start-up of the acidic BTF used 40 L of recycling liquid at pH 1.5 from the nutrient solution tank because it contains...
Acidithiobacillus sp. (Zhang et al. 2020). The BTF was operated in the down-flow condition. Initially, 40 L of recycling liquid was recirculated at 0.9 L/min along the packing material for 4 h without gas feeding, after which the flow rates of inlet gas was set to 18 L/min. After 2 weeks’ acclimation, the recycling liquid had stabilized at pH 0.9 and the variations in the inlet and outlet concentrations of H2S, D5, and D4 (Cin,H2S; in,D5; in,D4 and Cout,H2S; out,D5; out,D4) were measured. The corresponding loading rates (LRs), removal efficiency (REs) and elimination capacity (ECs) of H2S,D5, and D4 (LRH2S,D5,D4, REH2S,D5,D4 and ECH2S,D5,D4) were calculated based on these measurements and the detailed equations were described in our previous report (Zhang et al. 2020). The pH of the recycling liquid was adjusted daily to the set value (Table 1) using sodium hydroxide (NaOH) (Nacalai Tesque Inc., Kyoto, Japan). In addition to the irregular supply of water to the recycling liquid, 20 mL of mineral medium (elemental analysis: N, 6.618; P, 1,052; K, 1,120; Fe, 11.8; Mn, 0.4; Al, 1.0; Na, 25.4; Ca, 6.0; Mg, 9.8; S, 17.8; and B, 0.4 mg/L) was added daily into the nutrient solution tank.

The empty bed residence time (EBRT) is the length of time that gas spends in contact with the inside chamber of the BTF. As shown in Table 1, the EBRT was stable at 60 s through all operational stages in this study. Moreover, during day 110–111 in stage 4, the acidic BTF was operated under different EBRTs (18–106 s) to investigate the effect of EBRT on the REDS. On the 110th day, the EBRT was suddenly changed to 106 s from 60 s, and after the stable operation of the BTF for 1 h, the inlet and outlet gas were then sampled for measuring the Cin,D5 and Cout,D5. When the EBRT was changed in sequence from 106 s to 66 s, 53 s, 35 s, 27 s, 21 s, and 18 s, the same procedure was performed, i.e. gas sampling after 1 h of stable operation of the BTF. The same changes of EBRT were repeated on the 111th day. NaOH solution was added every hour to maintain the pH of the recycling liquid at 2.73.

### Table 1 | Performance data of the BTF as a function of pH

| Parameters          | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|---------------------|---------|---------|---------|---------|---------|
| Period (d)          | 0–38    | 39–78   | 79–104  | 105–124 | 125–149 |
| pH (−)              | 0.9 ± 0.05 | 1.2 ± 0.1 | 2.0 ± 0.3 | 3.0 ± 0.4 | 4.0 ± 0.2 |
| EBRT (s)            | 60      | 60      | 60      | 60      | 60      |
| Cin,H2S (ppmv)      | 425 ± 98 | 400 ± 87 | 429 ± 86 | 570 ± 27 | 436 ± 36 |
| Cout,H2S (ppmv)     | 0       | 0       | 0       | 0       | 0       |
| LRH2S (g/(m3·h))   | 18 ± 4  | 17 ± 4  | 18 ± 4  | 24 ± 1  | 18 ± 2  |
| REH2S (%)           | 100     | 100     | 100     | 100     | 100     |
| EC,H2S (g/(m3·h))  | 18 ± 4  | 17 ± 4  | 18 ± 4  | 24 ± 1  | 18 ± 2  |
| Cin,D5 (mg/m3)     | 3 ± 1   | 4 ± 2   | 6 ± 3   | 3 ± 2   | 6 ± 2   |
| Cout,D5 (mg/m3)    | 2 ± 0   | 3 ± 1   | 5 ± 2   | 3 ± 0   | 5 ± 2   |
| EC,D5 (mg/m3·h)    | 47 ± 7  | 36 ± 9  | 30 ± 7  | 17 ± 7  | 30 ± 12 |
| RE,D5 (%)          | 20 ± 13 | 17 ± 9  | 11 ± 9  | 8 ± 4   | 11 ± 2  |
| Cin,D5 (mg/m3)     | 19 ± 6  | 20 ± 8  | 28 ± 8  | 27 ± 6  | 27 ± 7  |
| Cout,D5 (mg/m3)    | 14 ± 4  | 16 ± 6  | 22 ± 9  | 23 ± 5  | 23 ± 8  |
| LRH2S (g/(m3·h))  | 1,182 ± 367 | 1,249 ± 512 | 1,691 ± 514 | 1,674 ± 396 | 1,626 ± 430 |
| RE,D5 (%)          | 26 ± 19 | 21 ± 13 | 18 ± 9  | 17 ± 3  | 12 ± 9  |
| EC,D5 (mg/m3·h)    | 316 ± 45 | 246 ± 20 | 324 ± 33 | 289 ± 29 | 222 ± 41 |

Note: Values are quoted as means ± standard deviation.

Partition tests

Mass transfer limitations are the main challenge to the efficient removal of siloxanes by BTFs (Popat & Deshusses 2008; Li et al. 2014; Santos-Clotas et al. 2019). A second phase can be used to improve the performance of a BTF for siloxanes abatement, e.g. oleyl alcohol (Popat & Deshusses 2008), biosurfactants (Li et al. 2014), and AC (Santos-Clotas et al. 2019). Furthermore, the time-dependent dimensionless partition coefficient and mass transfer coefficients (kL) are two important factors that govern the mass transfer process of siloxanes from biogas to the acidic BTF.
recycling liquid. Hence, partition tests for D5 between the gas and the recycling liquid of the BTF were conducted under different pH conditions according to the protocol reported in our previous study (Zhang et al. 2020). Samples of recycling liquids taken from the nutrient solution tank of BTF were directly used as the test liquids in partition tests; the pH of these samples ranged from 0.88 to 3.98 (Table 2). However, the liquid with pH 5.64 was obtained by diluting the recycling liquid with a pH 3.98 with deionized water rather than adding NaOH solution.

The initial D5 concentration in the headspace of 250 mL flasks containing 100 mL of the tested liquid was about 1,000 mg/m³. Several flasks were placed in a water-bath shaker at 30 °C and agitated at 150 times/min. At selected time intervals, the D5 concentrations in the headspace (\(C_G\)) and the liquid phase (\(C_L\)) of the flasks were measured and the corresponding gas–liquid partition coefficient of D5 were calculated according to Equation (1). According to the mass transfer model (Popat & Deshusses 2008), the mass transfer rate of D5 across a gas–liquid interface is expressed by Equation (2), which integrates to form Equation (3) as follows:

\[
P = \frac{\dot{C}_G}{\dot{C}_L} \quad (1)
\]
\[
V_G \frac{dC_G}{dt} = -k_L A \left( \frac{C_G}{P} - C_L \right) \quad (2)
\]
\[
C_G = c \cdot \exp \left( -\frac{k_L A}{V_G P} t \right) + C_L P \quad (3)
\]

where \(P\) is the partition coefficient, \(k_L\) is the mass transfer coefficient of D5 (m/h), \(V_G\) is the volume of the headspace of the flask (150 mL), \(C_G\) is the concentration (mg/m³) of D5 in the headspace, \(C_L\) is the equilibrium concentration (mg/m³) of D5 in the liquid phase, \(c\) is a constant, and \(A\) is the interfacial area for mass transfer in the flasks, which was estimated at 0.005 m².

### Extraction and analysis of siloxanes from liquid and gas samples

Siloxanes were extracted from the liquid before gas chromatography-mass spectrometry (GC-MS) analysis to determine their concentrations. First, 100 mL of recycling liquid sample and 50 mL of n-hexane (minimum purity 96%; Kanto Chemical Co. Inc., Tokyo, Japan) were added to a separating funnel, which was then shaken for 5 min. The mixture was treated with 8 g of anhydrous Na₂SO₄ to remove water, and the liquid was transferred to a conical flask and magnetically stirred at 1,000 rpm for 20 min (SR100; Toyo Roshi Kaisha, Ltd, Tokyo, Japan). After the mixture had been centrifuged (3,000 rpm, 3 min), the hexane layer was separated using a disposable pipette. In the case of gas samples, the siloxanes in adsorbents were Soxhlet-extracted with n-hexane for 10 h at 65 °C and then analyzed by GC-MS under the analytical conditions reported by Zhang et al. (2020).

### High-throughput sequence analysis of the microbial community

The microorganism community in the BTF at pH 1.5 was reported previously (Zhang et al. 2020). To better understand the evolution of the microbial community with increasing pH, the recycling liquid with pH 4.0 on day 150 was collected for 16S rRNA gene analysis. The DNA was extracted and purified using an Extrapol DNA Kit Plus v. 2 (Nippon Steel, Japan). The V4–V5 hypervariable regions of the 16S rRNA genes were polymerase chain reaction (PCR)–amplified using the universal primers U515F (5‘-GTGYCAGCMGC CGCGTGA-3’)

| Equilibration time (h) | 0.88 | 0.94 | 1.15 | 1.66 | 2.51 | 2.90 | 3.98 | 5.64 |
|-----------------------|------|------|------|------|------|------|------|------|
| 0.25                  | 2.3 ± 0.1 | 7.3 ± 2.0 | 18.4 ± 2.4 | 29.3 ± 3.7 | 23.5 ± 7.0 | 24.8 ± 2.9 | 6.3 ± 0.3 | 5.7 ± 0.8 |
| 0.5                   | 0.7 ± 0   | 4.9 ± 0.7 | 10.4 ± 2.0 | 22.7 ± 1.5 | 22.6 ± 7.0 | 19.8 ± 1.9 | 5.8 ± 0.3 | 5.8 ± 1.3 |
| 1.0                   | 0.4 ± 0.1 | 2.9 ± 0.8 | 5.6 ± 1.0 | 15.5 ± 2.0 | 15.7 ± 3.6 | 14.1 ± 1.1 | 4.9 ± 0.2 | 2.9 ± 1.0 |
| 2.0                   | 0.2 ± 0.1 | 2.4 ± 0.6 | 4.3 ± 0.1 | 10.6 ± 1.7 | 7.3 ± 0.8 | 8.3 ± 0.4 | 4.4 ± 0.2 | 2.2 ± 0.7 |
| 4.0                   | 0.2 ± 0   | 1.2 ± 0   | 2.0 ± 1.2 | 4.8 ± 0.3 | 4.6 ± 0.4 | 6.2 ± 0.3 | 4.3 ± 0.2 | 1.9 ± 0.6 |
| 16.0                  | -       | 0.9 ± 0.1 | 1.0 ± 0.5 | -     | -     | -     | -     | -     |
| 19.0                  | -       | -       | -       | 4.2 ± 0.2 | 3.5 ± 0.3 | 2.8 ± 0.1 | 3.1 ± 0.1 | 1.4 ± 0.4 |
and 926R (5'-CCGYCAATTCMTTTRAGTT-3'). The purified PCR amplicon was quantified using a PicoGreen dsDNA Assay Kit (Invitrogen, USA) and then pair-end sequenced by MiSeq (Illumina, USA).

The sequence data were processed using Quantitative Insights Into Microbial Ecology (QIIME) Pipeline (Caporaso et al. 2010). The sample was rarefied to exhibit the lowest number of reads (10,000 sequences) for alpha-diversity analyses, for which the rarefaction curves were generated from the observed species. Sequences were then phylogenetically assigned using the Greengene and Silva's Living Tree Database Project classifiers and allocated to phylum, class, family, and species levels (Zhang et al. 2020). Sequences were clustered into operational taxonomic units (OTUs) using a 97% identity threshold. Those OTUs with abundances exceeding 0.1% were selected to compare the microbial communities of the BTFs.

**RESULTS AND DISCUSSION**

**BTF performance as a function of pH**

After starting-up successfully at pH 0.9, the BTF was operated continuously under five different acidic conditions (pH 0.9, 1.2, 2.0, 3.0, and 4.0) for 150 days (Figure 1). The mean values of the corresponding parameters are shown in Table 1. The REH2S was stable at 100% and the ECH2S was in the range of 17–24 g/(m³·h) during operating stages 1–5, although Cin,H2S fluctuated within the range of 400–600 ppmv. Meanwhile, Cin,D5 and Cin,D4 maintained levels of 19–28 mg/m³ and 3–6 mg/m³, respectively. The RE,D5 and EC,D5 of the BTF at the same LR,D5 of 1,200 mg/(m³·h) or 1,700 mg/(m³·h) were compared; both showed decreasing trends with increasing pH. Table 1 shows that the RED5 decreased from 26% to 12% as the pH increased from 0.9 to 4.0. Meanwhile, the ECD5 decreased from 316 mg/(m³·h) to 246 mg/(m³·h) as the pH increased from 0.9 to 1.2 at the LR,D5 of 1,200 mg/(m³·h) and decreased from 324 mg/(m³·h) to 222 mg/(m³·h) as the pH increased from 2.0 to 4.0 at the LR,D5 of 1,700 mg/(m³·h).

Furthermore, the fluctuations in RED5 and ECD5 were attributed to changes in LR,D5 and pH and also to the variation in Cin,H2S. For example, lower Cin,H2S resulted in higher RED5 in the pH 0.9 case (2–14 day) and 1.2 case (39–57 day) (Figure 1). At extremely acidic pH values such as 0.9 and 1.2, the H2S was mainly biodegraded to S⁰ rather than to SO₄²⁻ due to the prevalence of F. acidiphilum (Zhang et al. 2020), i.e. deteriorated biodegradation of H2S led to sulfur deposition once the H2S concentration was too high. Sulfur deposition on the packing layer of the BTF blocked the mass transfer of siloxane from the gas to the recycling liquid. Therefore, lower Cin,H2S was beneficial for both H2S and siloxane abatement using the BTF under extremely acidic pH.

**Removal profiles of H2S**

Figure 2 shows the removal profiles of H2S and the LR,H2S for the BTFs under five acidic pH conditions. The experimental points were the Cout,H2S at different BTF heights and the corresponding RE,H2S. The lines in Figure 2 facilitate interpretation of the data. The Cout,H2S increased and the RE,H2S decreased with increasing LR,H2S for all tested pH conditions. Notably, 90% of the H2S removal was achieved during the first 0.4 m of the BTF. This observation is consistent with that of Tu et al. (2016), who found that H2S elimination occurred near the gas inlet section of the filter bed.
However, when the pH decreased from 4.0 to 1.2 and then to 0.9, the maximum $C_{\text{out,H}_2\text{S}}$ at 0.2 m of BTF decreased correspondingly from 150 ppmv to 60 ppmv, and then increased to 420 ppmv. Decreasing the pH to very low levels reduces $\text{H}_2\text{S}$ and $\text{O}_2$ solubility (Chaiprapat et al. 2014; Jaber et al. 2015). Similar variation was also observed in the RE$_{\text{H}_2\text{S}}$ because $\text{H}_2\text{S}$ removal is limited by the mass transfer of both $\text{H}_2\text{S}$ and $\text{O}_2$ under acidic conditions (Tu et al. 2016). Additionally, Figure 3 shows that 91.9% of the sequence reads in the pH 4.0 recycling liquid were associated with *Acidithiobacillus* sp., among which the relative abundances of *A. caldus* and *A. thiooxidans* were 83.6% and 8.3% respectively, while 85.5% of the sequence reads in the pH 1.5 recycling liquid belonged to *F. acidiphilum* (Zhang et al. 2020). Compared with the pH-neutral BTF (Montebello et al. 2015; Tu et al. 2016), our results indicate that an acidic BTF led to specialization of the bacterial community and the prevalence of *Acidithiobacillus* sp. However, excessively acidic pH led to the replacement of *Acidithiobacillus* sp. by *F. acidiphilum*, which is a major ferrous-iron oxidizing microbe (Zhang et al. 2020).

Moreover, the specific sulfur oxidation rate of the *A. thiooxidans* AZ11 and TAS cultures showed a maximum value at pH 1.3–1.5 and then decreased sharply with decreasing pH (Lee et al. 2006). In this study, a similar effect of pH is proposed for the sulfur oxidizing activity of *A. caldus* because it has a similar metabolism and ecophysiology to that of *A. thiooxidans* (Valdés et al. 2008). For *Acidithiobacillus* sp., the oxidation rate increased as the pH decreased from 4.0 to 1.2, and it exhibited a peak value near 1.2, and then decreased sharply as pH decreased to 0.9. Therefore, the excessively acidic pH of 0.9 blocked the mass transfer of $\text{H}_2\text{S}$ and $\text{O}_2$ from the gas to the recycling liquid. The low sulfur oxidation activity and low proportion of *Acidithiobacillus* sp. further aggravated the deterioration in biodegradation of $\text{S}^0$ to $\text{SO}_4^{2-}$.
Removal profiles of D5

Prolonging the gas–liquid contact time improves the mass transfer of siloxanes. Hence, increasing the EBRT is widely used to increase the siloxane RE of BTFs (Popat & Deshusses 2008; Santos-Clotas et al. 2019; Zhang et al. 2020). The effect of EBRT on the RE of the acidic BTF with pH 2.73 in stage 4 was investigated in this study (Figure 4). Similar to the result reported by Santos-Clotas et al. (2019), a positive correlation was observed between the D5 removal and EBRTs of 18–106 s, achieving the maximum D5 removal of 27.7% under the EBRT of 106 s. However, an EBRT of 10.1 min was required in a pH-neutral to achieve the same value of D5 removal (Santos-Clotas et al. 2019). This comparison indicates that acidic recycling liquid significantly improves gas-to-liquid mass transfer of D5.

Figure 5 presents the D5 removal profile of the BTF under different pH conditions. D5 removal decreased from 34.5% to 15.6% as the recycling liquid pH increased from 0.88 to 3.98. In our previous report, the removal of D5 in an acidic BTF was mainly attributed to absorption and further hydrolysis in the acid recycling liquid (Zhang et al. 2020). Therefore, the variation in D5 RE under different pH conditions resulted from changes in the absorption rate of D5 from the biogas into the recycling liquid, because lower acidic pH significantly promoted hydrolysis of D5 to silanol.

Mass transfer coefficient of D5 from gas to recycling liquid under different pH conditions

The variation in the partition coefficient of D5 between the gas and recycling liquid under different pH conditions together with the equilibration time is presented in Table 2. The stable partition coefficient after partition equilibrium increased from 0.2 to 3.1 as the pH increased from 0.88 to 3.98, and then decreased to 1.4 when the pH increased to 5.64. The variation in partition coefficient of D5 was related to the ionic strength of the recycling liquids, which changed with pH. During the daily operation of the BTF, some NaOH solution was added to the nutrient solution tank to adjust the recycling liquid pH to the set values (Table 1). Meanwhile, 20 mL of mineral medium was also added daily as a nutritional supplement for microbial growth. The addition of NaOH solution and mineral medium increases the total ionic strength of the recycling liquids. According to a previous report (Popat & Deshusses 2008), higher ionic strength mineral media increases the partition coefficient. Hence, a recycling liquid with higher pH had a higher partition coefficient: 0.2 for pH 0.88, 0.9–1.0 for pH 0.94–1.15, and 2.8–4.0 for pH 1.66–3.98. In the case of the pH 5.64, the addition of deionized water decreased the ionic strength of the recycling liquid, which led to a lower partition coefficient, 1.4.

The partition coefficient of D5 at the initial equilibration time of 0.25 h increased from 2.3 to 24.8 as the pH increased from 0.88 to 2.90, and then decreased to 6.3 at pH 3.98. The recycling liquid after long-term BTF operation contained some biomass flocs, which partly adsorbed D5. Generally, more biomass accumulated within the BTF operated under pH-neutral or lower acidic pH (Tu et al. 2017) because acidity inhibits the growth of many types of microorganisms (Tu et al. 2016). The total reads of microbial communities in the BTF recycling liquid at pH 1.5 and 3.98 were 31,800 and 47,267, respectively. The results indicate that more biomass accumulated in the BTF during operation at pH 3.98 than at pH 0.88–2.90. Therefore, the lower partition coefficient at pH values below 3.98 was attributed mainly to adsorption on the more numerous biomass flocs in the recycling liquid, although higher ionic strength also increased the partition coefficient.
Figure 6 | D5 profile in the flask headspace during the partition test as a function of equilibration time and pH.
Furthermore, the D5 concentration in the flask headspace was simulated using Equation (3) to obtain the $k_L$ of D5 in the BTF under different acidic pH conditions (Figure 6). Figure 7 and Table 3 show the various calculated $k_L$ values. The $k_L$ decreased rapidly from 0.075 m/h to 0.062 m/h when the pH increased from 0.88 to 1.15. In the pH range of 1.66–2.90, the $k_L$ decreased slowly from 0.060 m/h to 0.035 m/h, and finally decreased to 0.029 m/h when at pH 5.64. These results indicate that the mass transfer of D5 from the headspace gas to the liquid at the bottom of the flask was accelerated by the acidic recycling liquids, especially under extremely acidic pH conditions.

According to the model reported by Ottengraf & Van den Oever (1983), pollutant conversion can be calculated from the gas-phase mass balance of the pollutant at the height ($H$) of the BTF (Equation (4)). Considering that the $\delta$, $C_{in}$, $A_{bio}$, $U$, and $H$ of BTF were constant in this study, the D5 removal follows Equation (5), which was simplified from Equation (4) as follows:

$$\frac{C_{in} - C_{out}}{C_{in}} = \frac{h\delta A_{bio} H}{C_{in} U}$$  \hspace{1cm} (4)$$

$$RE = \alpha_1 k_L$$  \hspace{1cm} (5)

where $k$ is the kinetic coefficient (g/(m$^3_{biofilm}$·h)), $\delta$ is the biofilm thickness (m), $C_{in}$ and $C_{out}$ are the inlet and outlet pollutant concentrations (mg/m$^3$), $A_{bio}$ is the biofilm surface area per volume of packing material (m$^2_{biofilm}$/m$^3$ packing material), $U$ is the gas velocity (m/s), and $\alpha_1$ is a constant (h/m).

To quantify the contribution of $k_L$ for D5 removal, the calculated $k_L$ was correlated with the RE of D5 in the BTF under different pH conditions. Figure 8 shows that a positive linear relationship was obtained between the RE$_{D5}$ and $k_L$. Actually, hydrolysis of D5 in the acidic recycling liquid is the major reaction for D5 abatement in an acidic BTF. Hydrolysis is commonly recognized as the rate-limiting step, and the removal of D5 in an acidic BTF follows zero-order kinetics with reaction limitation (Ottengraf & Van den Oever 1983; Dumont 2017). Furthermore, the high $k_L$ values under extremely acidic pH conditions indicated a significant reduction in the resistance to gas–liquid mass transfer. Hence, it is feasible to decrease the pH of the recycling liquid for efficient D5 removal performance by an acidic BTF while simultaneously achieving high H$_2$S removal. Acid washing may be a promising alternative approach to remove siloxanes from biogas.

**CONCLUSIONS**

The performance of a BTF under different acidic pH conditions (0.9, 1.2, 2.0, 3.0, and 4.0) indicated that pH was a key parameter that directly affected operational
performance. The removal of D5 increased linearly with decreasing pH because the acidic recycling liquid accelerated the mass transfer of D5 in the BTF. However, the removal profile of H2S and the variation in the microbial community within the BTF indicated that excessively acidic pH blocked the mass transfer of H2S and O2 from the gas to the recycling liquid. The low sulfur oxidation activity and low proportion of Acidithiobacillus sp. also led to S0 deposition. The optimal pH was about 1.2, and under this acidic condition the BTF simultaneously achieved effective removal of H2S and D5 from biogas.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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