



## Effect of substrate sulfur state on MM and DMS emissions in landfill

Zhiyuan Jin<sup>a,b</sup>, Siyuan Zhang<sup>a,b</sup>, Lifang Hu<sup>c</sup>, Chengran Fang<sup>d</sup>, Dongsheng Shen<sup>a,b</sup>, Yuyang Long<sup>a,b,\*</sup>



<sup>a</sup> Zhejiang Provincial Key Laboratory of Solid Waste Treatment and Recycling, School of Environmental Science and Engineering, Zhejiang Gongshang University, Hangzhou 310012, China

<sup>b</sup> Instrumental Analysis Center of Zhejiang Gongshang University, Hangzhou 310018, China

<sup>c</sup> College of Quality and Safety Engineering, Institution of Industrial Carbon Metrology, China Jiliang University, Hangzhou 310018, China

<sup>d</sup> College of Civil Engineering, Zhejiang University of Technology, Hangzhou 310023, China

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### ABSTRACT

Methyl mercaptan (MM) and dimethyl sulfide (DMS) are typical landfill odorous gases that have received little attention compared with hydrogen sulfide (H<sub>2</sub>S). In this study, landfill MM and DMS emissions were investigated regarding their origin from substrates with different sulfur states, namely, intrinsic organic sulfur and external inorganic sulfur (SO<sub>4</sub><sup>2-</sup>). Substrates with high protein contents showed the highest potential for MM and DMS emissions, at 46.0 and 9.2 μL·g<sup>-1</sup> substrate, respectively. Meanwhile, a comparable contribution by SO<sub>4</sub><sup>2-</sup> was achieved when the SO<sub>4</sub><sup>2-</sup> content comprised over 40% of the substrate. The substrate contribution to DMS emission was up to 10 times the SO<sub>4</sub><sup>2-</sup> contribution. Meanwhile, the SO<sub>4</sub><sup>2-</sup> contribution to MM emission was over 1000 times that to DMS emissions. MM and DMS can accumulate in landfill sites and then be transformed into H<sub>2</sub>S or sulfide (S<sup>2-</sup>). This research offers a comprehensive understanding of MM and DMS emissions in landfill and provides a basis for classification management methods in landfill sites.

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### 1. Introduction

The generation of municipal solid waste has expanded in recent years, causing an increasing demand for appropriate disposal. Landfill remains a vital method of solid waste disposal (Liu et al., 2018a). However, odorous gases released from landfill sites are the subject of concern. Sulfur-containing odors are considered the main components of these odorous gases (Hu et al., 2017; Wu et al., 2017). Although many studies have focused on hydrogen sulfide (H<sub>2</sub>S), volatile organic sulfur compounds, such as methyl mercaptan (MM) and dimethyl sulfide (DMS), are also frequently detected in landfill sites (Wang et al., 2019). MM and DMS have very low thresholds of 0.07 and 5.9 ppm, respectively, with high concentrations, these odors are able to cause respiratory diseases or even lead to death. Therefore, the hazards posed by MM and DMS should not be neglected (Chen et al., 2017).

Previous studies have shown that MM and DMS can be generated by the decomposition of sulfur-containing organics, and in sulfate reduction processes by sulfate-reducing bacteria (SRB)

(Wu et al., 2010; Zhang et al., 2020). Landfill sites are complex man-made environments in which degradable substrates, including starch, cellulose, protein, and fat, coexist and serve as sulfur-containing organic sources (Zhao et al., 2017; Shao et al., 2019; Zhang et al., 2017). The emission of MM and DMS from continuous sulfate reduction processes (Long et al., 2016a, 2016b) in landfill sites needs special consideration.

Many studies have investigated assessment and removal methods for MM and DMS in landfill sites. The distribution of MM and DMS has been investigated in some real landfill sites, with concentrations varying among sites (Kim et al., 2006; Wu et al., 2017). MM was found to be the dominant odor at some landfill sites, with DMS also contributing to odor (Liu, et al., 2018b; Wang et al., 2019). MM and DMS concentrations decrease in the perimeter zone, but have been detected at sites 9000 m from landfill under suitable meteorological conditions (Liu, et al., 2018b). Furthermore, MM and DMS concentrations in landfill sites might fluctuate with the season (Lu et al., 2015). These studies have taken appropriate measures to acquire the MM and DMS concentrations using several field detection techniques, with a magnitude difference observed between them. This implies that countable MM and DMS detection times in landfill sites might not be sufficient for odor control. Meanwhile, the detailed emission behavior of MM and DMS has not received attention. In particular, the

\* Corresponding author at: Zhejiang Provincial Key Laboratory of Solid Waste Treatment and Recycling, School of Environmental Science and Engineering, Zhejiang Gongshang University, Hangzhou 310012, China.

E-mail address: [longyy@zjgsu.edu.cn](mailto:longyy@zjgsu.edu.cn) (Y. Long).

emission behavior and contribution of the combined processes of waste decomposition and sulfate reduction remain unknown (Chen et al., 2017), and the organic and inorganic sulfur precursors content of MM and DMS differ among landfill sites (Zhao et al., 2001; Sun & Barlaz, 2015). As ambiguity in the MM and DMS emission behavior will lead to increased difficulty in odor management and potential risks in landfill sites, the emission behavior of MM and DMS requires further study.

Herein, typical substrates containing intrinsic organic sulfur and external inorganic sulfur were selected to evaluate MM and DMS emission behavior by simulating landfill methods. This study aimed to provide a reference value for odor management strategies by elucidating typical odor emission behavior in landfill sites.

## 2. Materials and methods

### 2.1. Materials

MM and DMS emission behavior were first studied by simulating substrate degradation in the anaerobic landfill environment. Component analysis were conducted using samples from landfills, according to which typical sulfur-containing components, including animal proteins, plant proteins, vegetables, peels, carbohydrates, paper, garden waste, and textiles, were selected to contribute to the substrate. In this study, eggs, pork, tofu, cabbage, and rice purchased from a market were boiled before use as substrates. A4 copy paper, disposable buttonwood leaves, rubber bands, deadwood (buttonwood branches), white cotton, and flavedo were also selected as substrates. All substrates mentioned above were cut into pieces less than 1 cm in size.

The anaerobic granular sludge used for incubation was cultured at 35 °C before use. The sludge was considered active only if the organic dry weight (oTS) was more than half of the dry weight (DW). In this study, the oTS accounted for 81.46% of DW, making the sludge suitable for culture.

To further determine the contribution of inorganic sulfur to MM and DMS generation, four common organics, namely, starch, cellulose, protein, and fat, were mixed with contents of 11.1%, 25.4%, 24.4%, and 39.1%, respectively, to form a matrix. Soluble starch

and microcrystalline cellulose were used as the starch and cellulose, respectively, isolated soy protein powder was used as the protein, and powder oil was used as the fat (Du et al., 2014). Sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) was added to the monitored substrate to serve as the  $\text{SO}_4^{2-}$  source.

### 2.2. Experimental design

#### 2.2.1. Intrinsic organic sulfur test

The experimental setup is shown in Fig. 1. The effect of intrinsic organic sulfur on MM and DMS emissions in landfill was investigated using 24 anaerobic bottles (100 mL) as reactors. Two parallel reactors were used for each substrate and the control check (CK) group. The reactors were named according to the substrates added. Substrate, sludge (40 g), and deionized water (10 mL) were added to each reactor. The amount of each substrates added was calculated according to the amount of anaerobic sludge added to ensure that the oTS of each substrate was less than half of the oTS in the sludge. Therefore, the wet weights (WWs) of boiled eggs, cooked pork, copy paper, boiled tofu, cooked rice, flavedo, cabbage, broken leaves, crushed rubber bands, deadwood, and broken cotton used were 5.1, 5.1, 10.1, 7.9, 2.5, 5.05, 1.5, 2.0, 1.4, 1.7, and 1.5 g, respectively. After inserting a rubber plug and twisting the bottle cap closed, nitrogen was blown into reactors for 5 min to remove oxygen. All reactors were then placed into a shaker operated at 35 °C and 120 rpm.

#### 2.2.2. External inorganic sulfur test

The effect of external inorganic sulfur on MM and DMS emissions in landfill was investigated using 40 anaerobic bottles (80 mL) as reactors. The reactors were divided into two groups, named R1 (without  $\text{SO}_4^{2-}$  addition) and R2 (with  $\text{SO}_4^{2-}$  addition). Each group comprised 20 parallel bottles, denoted Ri-01 to Ri-20 ( $i = 1$  or 2). Each reactor was filled with mixed substrate (10 g) and mixed anaerobic sludge (2 mL), as described in Section 2.1. In group R1, deionized water (20 mL) was then added to each reactor to simulate leachate without an inorganic sulfur source. Meanwhile, in group R2,  $\text{Na}_2\text{SO}_4$  solution (20 mL, 7.5 g/L) was added to each reactor to simulate leachate containing  $\text{SO}_4^{2-}$ , so that the  $\text{SO}_4^{2-}$

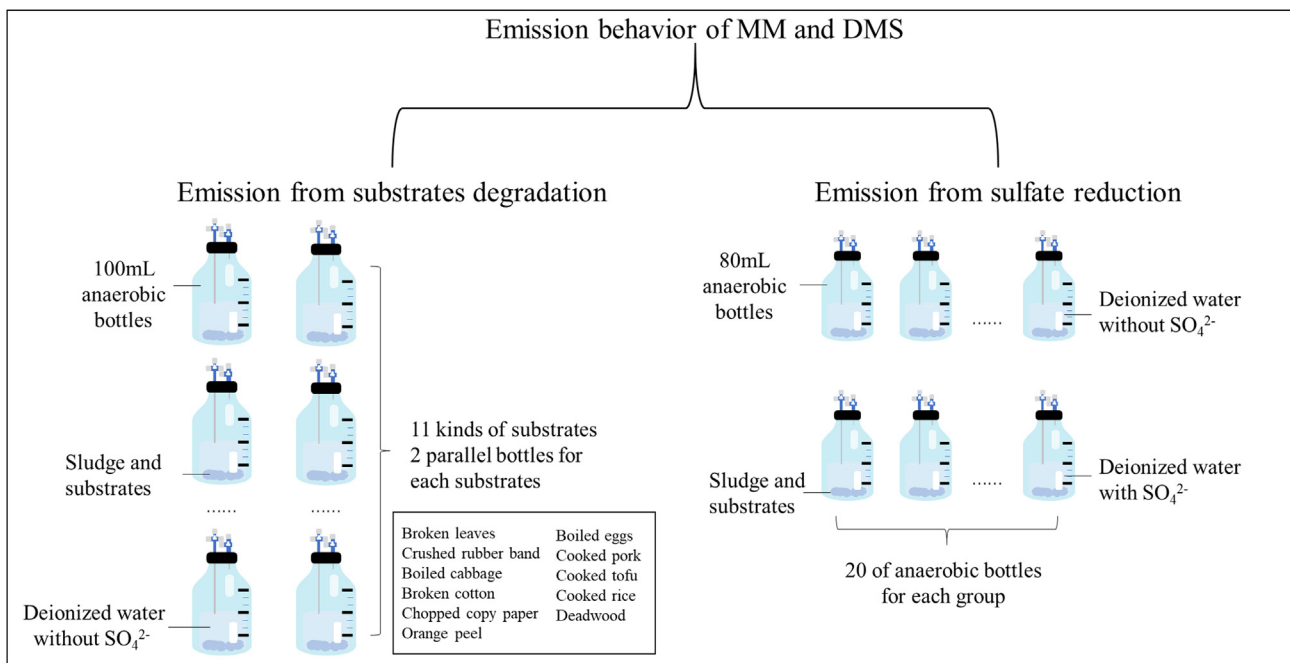


Fig. 1. Experimental design of the study.

content would be close to that in the sample mentioned in Section 2.1. The bottles were sealed and then treated as described in Section 2.2.1.

### 2.3. Analysis

Syringes were used for gas sampling in all tests. A 50-mL syringe was connected to the reactors such that internal gas could be taken into the syringe until the pressure inside the syringe and reactor reached atmospheric pressure. The gas volume was recorded according to the scale on the syringe, and the gas was then transferred into a corresponding aluminum foil bag. The collected gas could also be sampled immediately if necessary. Every 2–10 days (adjusted according to gas generation), two reactors were selected randomly from each group, and gas collected from the reactors and corresponding foil bags was sampled, with the concentrations recorded as  $C_R$  and  $C_B$ , respectively. The gas volume in the headspace of the reactors and corresponding foil bags was measured as  $V_R$  and  $V_B$ , respectively, allowing total  $H_2S$ , MM, or DMS generated during the experiment period to be calculated using Eq. (1):

$$V_T = C_R \times V_R + C_B \times V_B \quad (1)$$

After sampling, the reactors were opened, and  $S^{2-}$  and  $SO_4^{2-}$  concentrations in the solid and liquid phase were determined. The bottles were sealed, and nitrogen was blown again after solid and liquid sample was taken.

The  $H_2S$ , MM, DMS,  $SO_4^{2-}$ , and  $S^{2-}$  concentration determination methods are described in previous studies (Fang et al., 2016; Ying et al., 2019). Gas chromatography with a flame photometric detector was used to determine  $H_2S$ , MM, and DMS concentrations, while ion chromatography with an electrolytic conductivity detector was used to determine the  $SO_4^{2-}$  concentration. DMDS was also detected using the same gas chromatography, however there was no signal during all testing. Therefore, we considered the DMDS concentration was always below the detection limit, and it is not discussed in the results.

The DW, WW, and oTS of the substrate and sludge were measured according to the mass or the mass loss after heated under 70 °C and 600 °C, in accordance with the previous report (Yu et al., 2018). All sampling and analyzing methods were performed in triplicate.

## 3. Results and discussion

### 3.1. Effect of intrinsic organic sulfur in substrates on MM and DMS emissions

The effect of intrinsic organic sulfur in substrates on MM and DMS emissions was studied initially. The variation in MM and DMS concentrations is shown in Fig. 2. MM and DMS emissions from organic sulfur in the microorganisms could be ignored because hardly any MM and DMS was observed in the CK group. The MM and DMS concentrations were consistently low in some reactors, including those containing copy paper, crushed leaves, deadwood, and broken cotton, which mainly consisted of cellulose and lignin. These substrates were partially degraded by microorganisms because the average oTS losses of copy paper, crushed leaves, deadwood, and broken cotton were 47.33%, 25.98%, 10.19%, and 41.9% of the original oTS, respectively. Therefore, the low emission concentrations in these reactors was likely due to the low sulfur contents in the substrates. Crushed rubber band, which possessed a higher sulfur content, also showed low MM and DMS emissions. However, this was attributed to low microbial utilization because the oTS loss was below the detection limit.

In contrast, the concentration in other reactors changed distinctly with time. The MM and DMS concentrations reached a maximum in a short time in reactors containing boiled eggs, cooked pork, boiled cabbage, and cooked tofu as substrates. The corresponding maximum MM concentrations were 543.75, 139.75, 982.1, and 1300.6 ppmv, respectively, while the corresponding maximum DMS concentrations were 39.2, 24.8, 118.9, and 136.4 ppmv, respectively. The concentration declined rapidly thereafter, which might be due to the emission of  $CH_4$  and other gases, whose

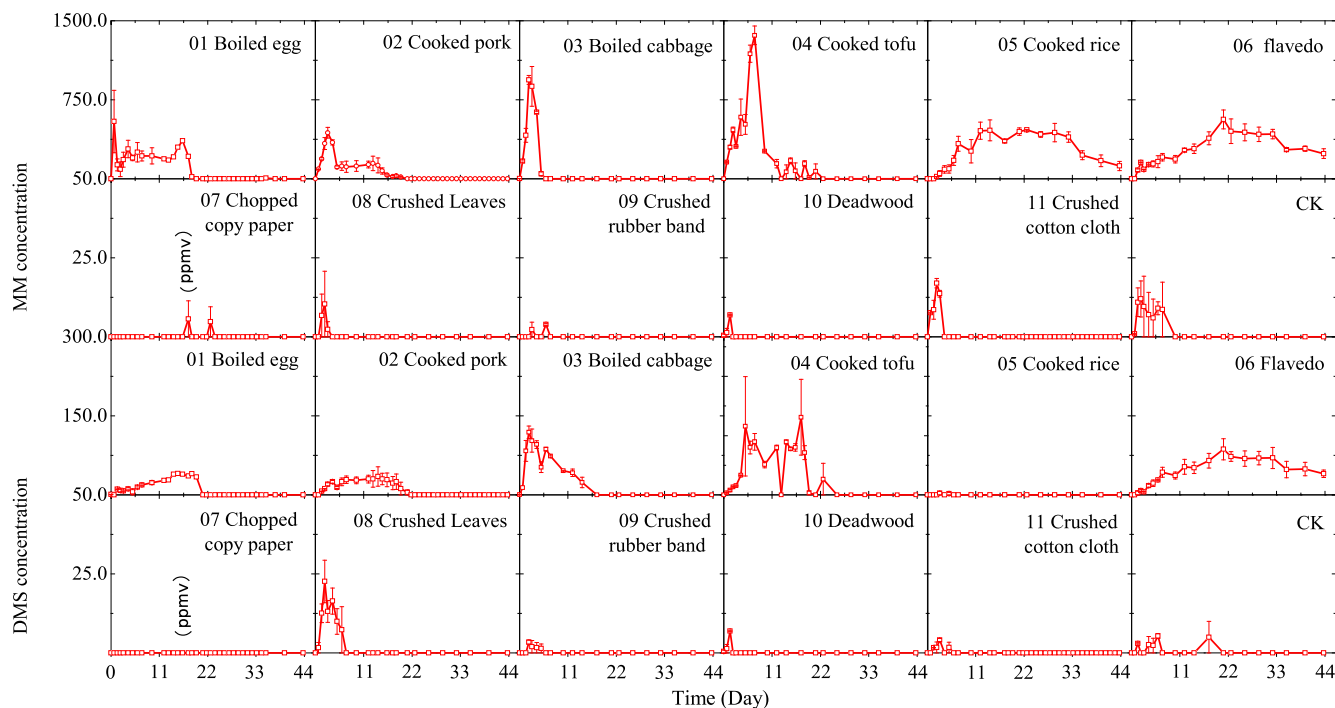


Fig. 2. Effect of intrinsic organic sulfur on MM and DMS emission.

generation volume could reach over 100 mL, this would dilute MM and DMS. For cooked tofu as substrate, a decrease in  $\text{CH}_4$  generation induced a second increase in DMS concentration. While MM concentration was not increased since the emission rate of it was also decreased. Compared with these four substrates, the MM and DMS concentrations in the reactors containing cooked rice and flavedo remained relatively high for a long time. This was attributed to low gas generation, resulting in low influence on the MM and DMS concentrations.

Overall, the MM and DMS release rate was different among the various substrates. A high MM concentration was usually accompanied by a high DMS concentration, and the DMS concentration was usually lower than the MM concentration in the same reactor. These phenomena were mainly observed in food wastes with high organic sulfur contents, in agreement with previous studies (Wu et al., 2010; Zhang et al., 2020). High degradability was also a key factor in the higher MM and DMS emission rates. Therefore, an increase in these types of waste can cause high concentrations of MM and DMS in landfill in a short time.

### 3.2. Effect of external inorganic sulfur in substrates on MM and DMS emissions

As shown in Section 3.1, intrinsic organic sulfur in substrates caused fluctuations in the MM and DMS concentrations. Therefore, an easily degraded substrate was used and monitored to study the effect of inorganic sulfur on MM and DMS emissions. MM and DMS emissions in the presence of different initial  $\text{SO}_4^{2-}$  contents are shown in Fig. 3. In accordance with the easily degraded substrates in Section 3.1, MM and DMS were generated in the reactors. In both initial environments, MM and DMS concentrations reached maxima on day 24 after reactor setup.  $\text{SO}_4^{2-}$  addition did not affect

the time at which the maximum concentration occurred, but influenced the peak concentration values. The maximum MM and DMS concentrations were 477.0 and 5.6 ppmv when no  $\text{SO}_4^{2-}$  was added, and 922.0 and 14.2 ppmv when  $\text{SO}_4^{2-}$  was added to the substrates, respectively. The emission speed gradually slowed after the maxima, with the concentration gradually decreasing (see Fig. 3).

In conclusion,  $\text{SO}_4^{2-}$  in landfill might also increase MM and DMS concentrations rather than increase the generation speed, almost doubling the maximum MM and DMS concentrations. This showed that the methylation of  $\text{H}_2\text{S}$  occurred during sulfate reduction processes in landfill sites. Therefore, the MM and DMS concentrations can also exceed standard levels if the  $\text{SO}_4^{2-}$  concentration is sufficiently high.

### 3.3. Contribution of organic and inorganic sulfur in substrates to MM and DMS accumulation

As discussed in Sections 3.1 and 3.2, differences in both organic and inorganic sulfur led to discrepancies in MM and DMS emission behavior. To determine the contribution rate of organic and inorganic sulfur to MM and DMS emissions, the accumulation of MM and DMS from substrates and  $\text{SO}_4^{2-}$  was measured. The accumulation of MM and DMS from various substrates is shown in Fig. 4. The accumulation volumes on day 24 were used as all reactors reached concentration maxima within 500 h. As mentioned in Section 3.1, six types of food waste, namely, boiled eggs, cooked pork, boiled cabbage, cooked tofu, rice, and flavedo, showed greater potential for biochemical MM production. Among them, cooked tofu, which is protein-rich and plant-based, showed the highest MM production potential. Each gram of cooked tofu produced  $46 \pm 0.1 \mu\text{L}$  of MM. Meanwhile, the MM release potentials of eggs, pork, cabbage, rice, and flavedo were  $36.7 \pm 0.0$ ,  $23.2 \pm 7.0$ ,  $28.6 \pm 0.4$ ,  $25.1 \pm 1.2$ , and  $15.6 \pm 2.0 \mu\text{L}\cdot\text{g}^{-1}$ , respectively.

These substrates, except rice, showed high DMS emission abilities. Cooked tofu showed the highest DMS production potential, with  $9.2 \pm 2.3 \mu\text{L}$  of DMS generated per gram. Meanwhile, the DMS emission potentials of eggs, pork, cabbage, and flavedo was  $3.0 \pm 0.0$ ,  $4.5 \pm 2.3$ ,  $2.8 \pm 2.0$ , and  $2.2 \pm 0.5 \mu\text{L}\cdot\text{g}^{-1}$ , respectively. Furthermore, although broken leaves and deadwood as substrates produced low DMS concentrations, both showed DMS production potential, at  $1.4 \pm 0.4$  and  $0.8 \mu\text{L}\cdot\text{g}^{-1}$ , respectively. In conclusion, substrates with easily degradable organics might result in higher MM and DMS accumulation.

To confirm the contribution of organics to MM and DMS emission, the ratios of MM and DMS yields to oTS and oTS consumption were calculated, as shown in Table 1. The highest ration was shown in bold letters. Boiled cabbage and cooked tofu showed the highest MM and DMS production abilities per gram of oTS, respectively, of 379.3 and  $9.5 \mu\text{L}\cdot\text{g}^{-1}$ . This indicated that the low oTS in boiled cabbage can produce a considerable amount of MM. The difference in MM emission contributions between substrates and oTS indicated that specific organics make a greater contribution to odor generation, with amino acids confirmed to be an important source that can generate various odors with different structures (Du and Parker, 2012).

Next, the contribution of inorganic sulfur to MM and DMS accumulation was studied. MM and DMS accumulation in reactors with or without initial  $\text{SO}_4^{2-}$  addition is shown in Fig. 5. In group R1, the cumulative production of MM and DMS gradually increased in the reactor, with MM reaching the peak value of  $33.9 \mu\text{L}$  on day 57, while DMS reached the peak value of  $0.50 \mu\text{L}$  on day 7. A similar phenomenon was observed in the environment containing  $\text{SO}_4^{2-}$  (R2). The maximum MM and DMS accumulations were 45.7 and  $0.71 \mu\text{L}$  on day 24. This indicated that the peak values of MM and DMS production were restricted by the total amount of initial sulfur sources in the system. The addition of  $\text{SO}_4^{2-}$  increased the

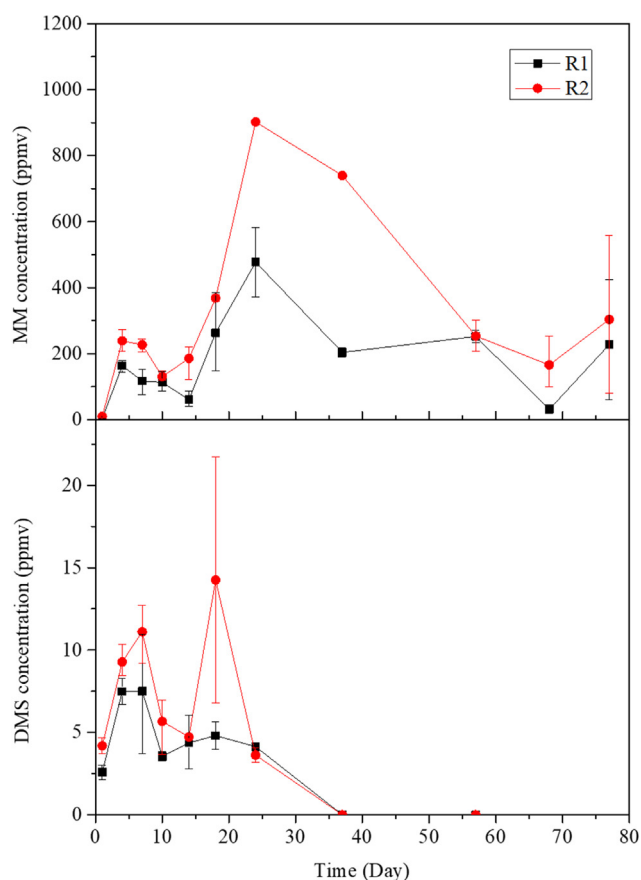


Fig. 3. Effect of external inorganic sulfur on MM and DMS emission.

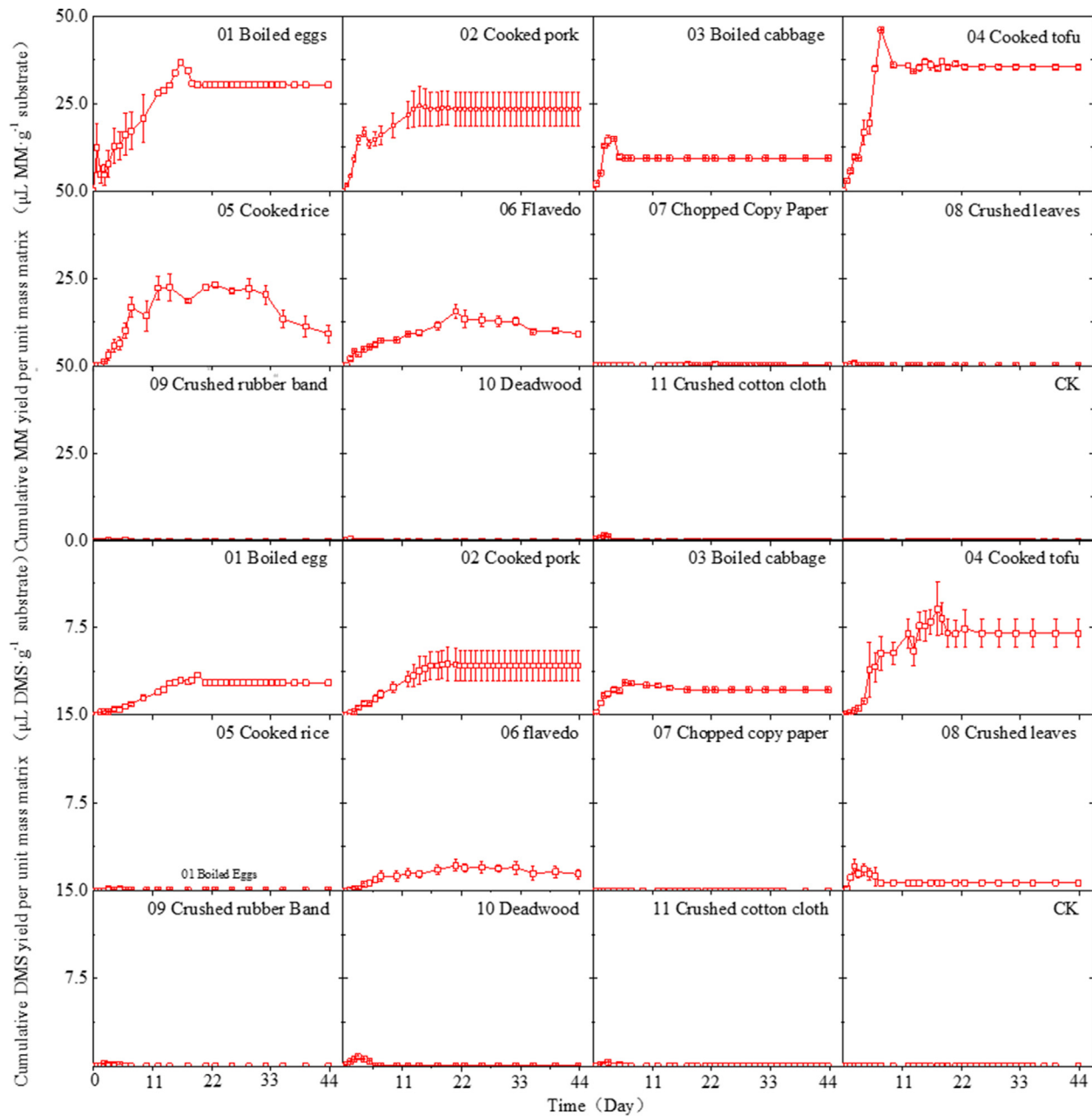


Fig. 4. Contribution of organic sulfur in substrate to MM and DMS accumulation.

**Table 1**  
Ratio of MM and DMS yield to substrate matter,  $\sigma\text{TS}$  and  $\sigma\text{TS}$  consumption ( $\mu\text{L} \cdot \text{g}^{-1}$ ).

No.	Substrate	MM/substrate	DMS/substrate	MM/ $\sigma\text{TS}$	DMS/ $\sigma\text{TS}$
01	Boiled egg	36.7	3	168.3	2.7
02	Cooked Pork	24.5	4.5	73.9	2.4
03	Boiled cabbage	15.5	2.8	<b>379.3</b>	6.8
04	Cooked Tofu	<b>46.0</b>	<b>9.2</b>	304.7	<b>9.5</b>
05	Cooked Rice	25.1	0	54.8	0
06	flavored	15.6	2.2	83.6	2.3
07	Chopped copy paper	0	0	0	0
08	Crushed leaves	0	1.4	0	1
09	Crushed rubber band	0	0	0	0
10	Deadwood	0.5	0.8	0.6	0.6
11	Broken cotton	1.5	0.4	1.5	0.3



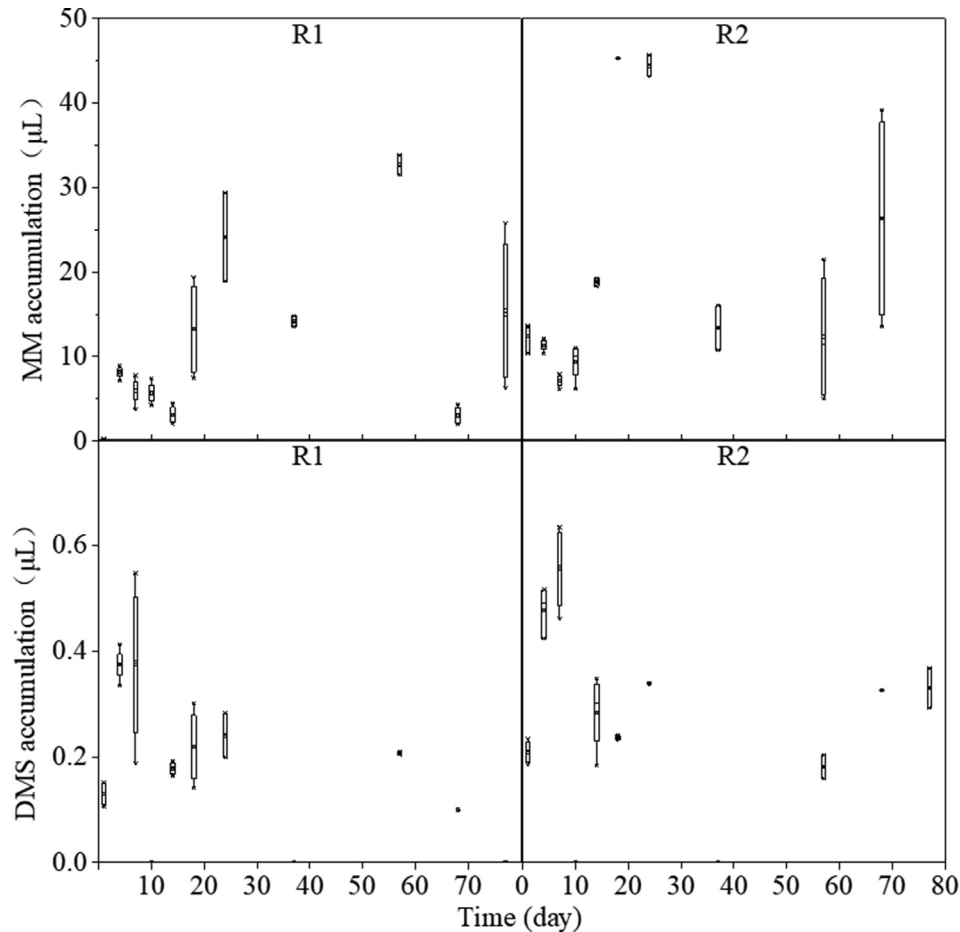


Fig. 5. Accumulation of MM and DMS without (R1) or with (R2) initial inorganic sulfur addition.

Table 2

Ratio of MM and DMS yield to inorganic sulfate.

	H <sub>2</sub> S	MM	DMS
Accumulation difference caused by sulfate (μL)	26.4	11.8	0.09
Ratio of H <sub>2</sub> S, MM and DMS yield to SO <sub>4</sub> <sup>2-</sup> (μL·g <sup>-1</sup> )	275.0	122.9	0.94

content of MM and DMS released, with the contribution of SO<sub>4</sub><sup>2-</sup> to MM and DMS emissions shown in Table 2. The contribution of SO<sub>4</sub><sup>2-</sup> to MM emission was 122.9 μL·g<sup>-1</sup>, which was significant if the masses of substrate and SO<sub>4</sub><sup>2-</sup> were similar. However, SO<sub>4</sub><sup>2-</sup> rarely reached this content. The contributions of SO<sub>4</sub><sup>2-</sup> and substrates to MM emission are comparable when SO<sub>4</sub><sup>2-</sup> accounts for around 10%–40% of the total substrate mass. In contrast, the contribution of SO<sub>4</sub><sup>2-</sup> to DMS emission was 0.94 μL·g<sup>-1</sup>, showing that the contribution of SO<sub>4</sub><sup>2-</sup> to MM emission was over 1,000 times the contribution to DMS emission. Therefore, DMS was mainly produced by the degradation of substrates, as shown in Tables 1 and 2. Notably, the highest DMS emission contribution from the substrate was around 10 times that from SO<sub>4</sub><sup>2-</sup>.

These phenomena emphasized the importance of determining the main source of odors, and the adoption of proper waste sorting management in landfill sites. Sufficient attention should be given to food waste, especially waste with a high protein content. As food waste has a high utilization potential, sorting some waste for further applications is highly recommended. However, the SO<sub>4</sub><sup>2-</sup> content in waste should be analyzed before entering landfill. If waste has a SO<sub>4</sub><sup>2-</sup> content over 10%, it should be considered unsuitable for landfill, or the SO<sub>4</sub><sup>2-</sup> content should be reduced to a safe amount.

Accumulation was found to decrease in some reactors before or after peak values were reached, which should mainly be caused by the transformation of MM and DMS into other types of sulfur. To determine the fate of MM and DMS, some other forms of sulfur were detected simultaneously.

#### 3.4. Transformation of sulfur during MM and DMS emission processes

MM and DMS formation processes in the reactors can be regarded as the mutual transformations of various sulfur-containing substances in the system. The high contribution of SO<sub>4</sub><sup>2-</sup> to H<sub>2</sub>S and MM emissions, as shown in Table 2, indicated various transformation pathways from SO<sub>4</sub><sup>2-</sup>. Some SRB are thought to convert MM and DMS into H<sub>2</sub>S or S<sup>2-</sup> through demethylation, as shown in Eq. (2) (Bentley & Chasteen, 2004). In group R1 and R2 reactors, S<sup>2-</sup> and H<sub>2</sub>S were detected, with the contents shown in Fig. 6. The phenomenon of H<sub>2</sub>S accumulation in the two groups experienced an initial growth, and then remained relatively stable or declined after reaching the peak. H<sub>2</sub>S in reactors without SO<sub>4</sub><sup>2-</sup> reached cumulative peak values on day 10, at 115.4 μL. The peak value was 141.8 μL on day 24, when additional SO<sub>4</sub><sup>2-</sup> was present. More abundant initial sulfur sources increased the time taken for conversion to H<sub>2</sub>S and increased the final emission amount. Decreased H<sub>2</sub>S accumulation was accompanied by decreased MM and DMS. In group R1, the peak value of MM appeared later than that of H<sub>2</sub>S, indicating that H<sub>2</sub>S was not the final form of MM and DMS, and that mutual transformation occurred.

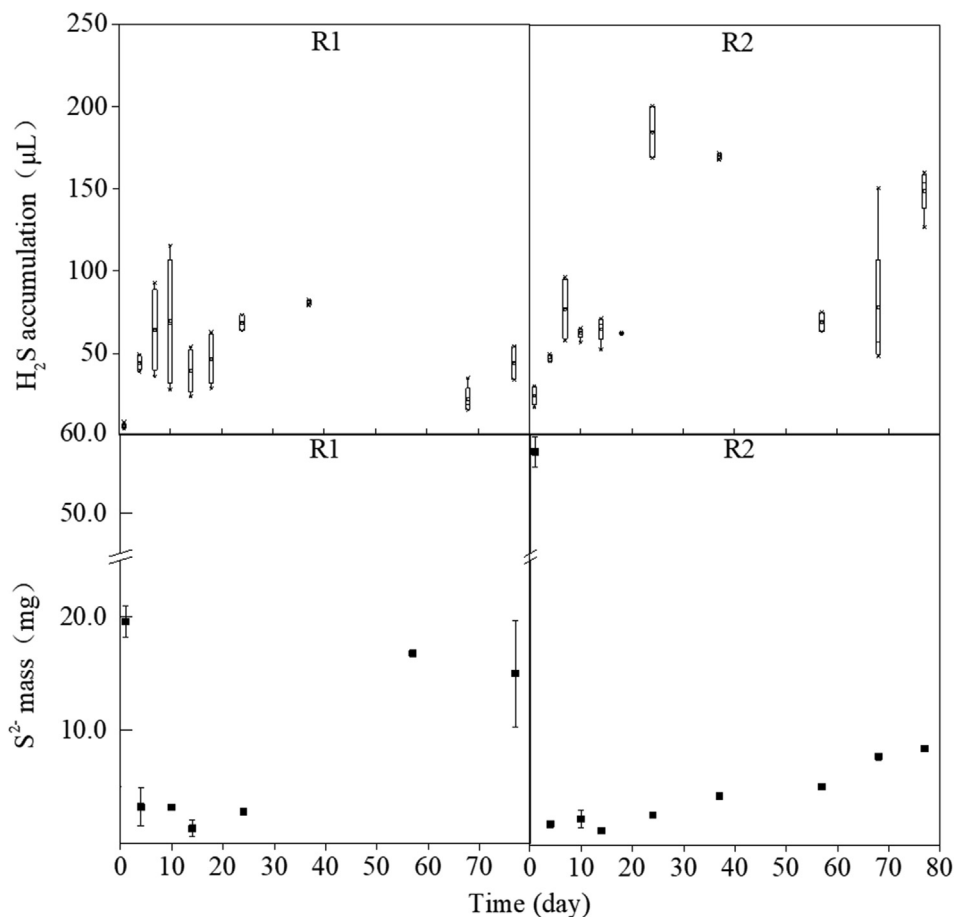
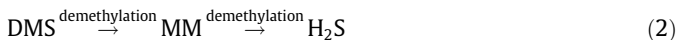


Fig. 6. Accumulation of H<sub>2</sub>S and sulfide without (R1) or with (R2) initial inorganic sulfur addition.



S<sup>2-</sup> is formed by direct SO<sub>4</sub><sup>2-</sup> reduction or through dissolution of H<sub>2</sub>S. In group R2 with SO<sub>4</sub><sup>2-</sup> addition, the S<sup>2-</sup> content increased from around 20 mg to 57.4 mg in a relatively short time. However, after 4 days, the S<sup>2-</sup> mass was decreased to less than 5 mg and remained at this level. Since not all forms of sulfur were detected, difficulties exist here in explaining the transformation of sulfide. After 24 days, the amount of S<sup>2-</sup> began to recover, reaching 13.8 mg on day 77. In group R1 without initial SO<sub>4</sub><sup>2-</sup>, the maximum S<sup>2-</sup> content was lower, at 20.9 mg, and the final S<sup>2-</sup> mass recovered to 16.8 mg on day 77. Notably, in groups R1 and R2, the S<sup>2-</sup> content began to recover on days 14 and 24, respectively, which were close to the H<sub>2</sub>S peak, and MM and DMS accumulation was observed, as mentioned earlier. This indicated that S<sup>2-</sup> was a terminal product after MM and DMS were generated, in agreement with previous studies (Long et al., 2017; Zhang et al., 2017). However, the S<sup>2-</sup> content in reactors with SO<sub>4</sub><sup>2-</sup> addition was slightly lower than in reactors without SO<sub>4</sub><sup>2-</sup> addition, indicating that other sulfur forms other than S<sup>2-</sup> might also be generated (Shen et al., 2015). These processes reflected the physicochemical environment within the system to some extent, and high DMS and MM emissions might lead to potential risks when converted into other forms. Therefore, controlling MM and DMS emissions from the source is of vital importance.

#### 4. Conclusions

This study expands the understanding of MM and DMS release behavior in landfill sites. The results showed that MM and DMS emissions in landfill were the combined result of substrate degra-

dation and sulfate reduction processes. With no limits to waste entry, high contents of protein and SO<sub>4</sub><sup>2-</sup> in landfill can cause elevated MM and DMS pollution. The influence of SO<sub>4</sub><sup>2-</sup> might exceed that of substrates if SO<sub>4</sub><sup>2-</sup> comprises over 20% of the content. The contribution of substrates to DMS emission was around 10 times higher than that of SO<sub>4</sub><sup>2-</sup>, while the contribution of SO<sub>4</sub><sup>2-</sup> to MM emission was over 1,000 times higher than the contribution to DMS emission. Furthermore, MM and DMS can be mutually inter-converted with H<sub>2</sub>S, and finally transformed to S<sup>2-</sup>, which might lead to other hazards. Therefore, appropriate management, such as forbidding substrates with high SO<sub>4</sub><sup>2-</sup> or organic sulfur contents to enter landfill, should be conducted.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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