Simultaneous biodegradation of dimethyl sulfide and 1-propanethiol by *Pseudomonas putida* S-1 and *Alcaligenes* sp. SY1: “Lag” cause, reduction, and kinetics exploration

Qian Li1,2 · Zeqin Tang3 · Jiahui Zhang1 · Jingtao Hu3 · Jianmeng Chen1,2,3 · Dongzhi Chen1,2,3

Received: 12 November 2021 / Accepted: 15 February 2022 / Published online: 23 February 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract

Simultaneous biodegradation of malodorous 1-propanethiol (PT) and dimethyl sulfide (DMS) by *Pseudomonas putida* S-1 and *Alcaligenes* sp. SY1 was investigated and the interactions implicated were explored. Results showed that PT was completely degraded in 33 h, while a lag of 10 h was observed for DMS degradation alone, and the lag was even extended to 81 h in the binary mixture. Mechanism analysis found that the lag was mainly attributed to the exposure of DMS degrader (*Alcaligenes* sp. SY1), rather than PT metabolites and PT degrader. The exposure time and PT concentration also influenced the lag duration much. Citric acid could effectively reduce the lag. Pseudo-first-order model was proved suitable for the description of PT degradation, revealing that PT degradation could be enhanced in presence of DMS with a concentration of < 50 mg L\(^{-1}\). A modified Gompertz model, incorporated the lag phase, was developed for the description of DMS degradation in the mixture, revealing that DMS degradation depended on the initial PT concentration, and when the lag was not considered, PT with low-concentration could promote DMS biodegradation, while a higher concentration (> 20 mg L\(^{-1}\)) cast negative effect.

Keywords Simultaneous biodegradation · 1-Propanethiol · Dimethyl sulfide · Lag reduction · Kinetics

Introduction

Volatile organic compounds (VOCs) are widely considered as major precursors for the photochemical smog and haze, imposing great threats on environment quality and human health. As a typical kind of VOCs, volatile organic sulfur compounds (VOSCs) are highly toxic and malodorous with extremely low smell threshold (Padhi and Gokhale 2017). They are not only the main composition of traditional malodor sources, i.e., waste water treatment plants, waste landfills, livestock, and poultry farm etc., but also closely related with pharmaceutical chemicals, petroleum refineries, papermaking, and other industries (Giri and Pandey 2013; Giri et al. 2014). So far, many treatment technologies, like condensation, UV oxidation, regenerative thermal oxidation, catalytically incineration, adsorption etc., have been employed for the disposal of odorous and hazardous organic compounds (Durme et al. 2008; Zhang et al. 2017). Thereinto, biotechnology is one of the most applicable ways for the purification of VOSCs, due to its various advantages of ecological, low cost and no secondary pollution, etc., especially for the waste gas with high-volume and low-concentration (Jo and Shin 2010; Qiu and Deshusses 2017; Kennes and Veiga 2013).

To date, numerous microorganisms have been acclimated and isolated for the degradation of VOSCs. These microorganisms are usually highly specific; only one or one kind of VOSC compounds can be efficiently degraded. However, multiple waste gases usually coexist in practical situations. Unknown interactions are likely to occur during their degradation processes, which may largely influence their original degradation behaviors. It was reported that the removal of dimethyl sulfide (DMS) was affected by the presence of methyl mercaptan and H\(_2\)S (Wani, Lau, and Branion 1999;
Li et al. 2003). In addition, substrate interactions, including co-metabolism, sequential degradation, competitive inhibition, uncompetitive inhibition, and noncompetitive inhibition, were also observed in many studies (Chen et al. 2008; Chen et al. 2007; Chen et al. 2018; Zhou et al. 2011). Chignell et al. claimed that an antagonistic interaction existed between P. putida KT2440 and Bacillus atrophaeus 1942 when co-cultured on agar plates (Chignell et al. 2018). To be noted, negative effects (inhibition), rather than positive effects (enhancement), were more frequently reported when several kinds of gases were simultaneously degraded (Yang et al., 2016; Bielefeldt and Cort 2005).

DMS and 1-propanethiol (PT) are two typical malodorous VOSCs in industrial parks (Han et al. 2018; Ras, Borrull, and Marcé 2008). However, researches on their simultaneous removal were very limited. Recently, a solid composite microbial inoculant composed of Alcaligenes sp. SY1 and P. putida S-1 was successfully prepared, which showed improved removal performance and shortened start-up period, when inoculated in biotrickling filters (Chen et al. 2018). Nevertheless, the interactions involved in their degradation process have not yet been elucidated.

Degradation kinetic study is an important analytical method to unveil the mechanism involved substrate interactions. The Monod model is usually used in investigating the non-inhibitory biomass growth of a pure culture with restricted substrate (Pala-Ozkok et al. 2012), and the effects of substrate inhibition on biomass growth at high concentrations have been described by a special model based on Monod or another model (Pala-Ozkok et al. 2015). Nevertheless, the interactions involved in the degradation process have not yet been elucidated.

Materials and methods

Chemicals and reagents

The chemicals used for culture were of analytical grade, the chemicals/solvents used for gas chromatographic analysis were of chromatographic grade, and the odorant compounds DMS and PT were in liquid form (> 99%). The mineral medium (MM) used in the batch experiment was composed of 4.5 g L⁻¹ Na₂HPO₄·12H₂O, 1.0 g L⁻¹ KH₂PO₄, 1.5 g L⁻¹ NH₄Cl, 0.023 g L⁻¹ CaCl₂, 0.2 g L⁻¹ MgCl₂, and 1 mL of trace element stock solution. The trace element stock solution contained 1.0 g L⁻¹ FeSO₄·7H₂O, 0.02 g L⁻¹ CuSO₄·5H₂O, 0.014 g L⁻¹ H₃BO₃, 0.10 g L⁻¹ MnSO₄·4H₂O, 0.10 g L⁻¹ ZnSO₄·7H₂O, 0.02 g L⁻¹ Na₂MnO₄·2H₂O, and 0.02 g L⁻¹ CoCl₂·6H₂O. The pH of the medium was adjusted to 7.0 by using phosphate buffer solution. All chemicals and reagents were purchased from Aladdin Reagent Co., Ltd. (Shanghai, China).

Microorganisms and culture conditions

Alcaligenes sp. SY1, a Gram-negative aerobic heterotrophic bacterium with DMS-degrading ability, was isolated from activated sludge collected from Zhejiang Huahai Pharmaceuticals Co., Ltd. (Linhai, Zhejiang, China) (Sun et al. 2016). P. putida S-1 was reported as the first P. putida strain capable of degrading malodorous PT (Chen et al. 2016). These two strains were stored in China Center for Type Culture Collection under CTCC Nos. M 2014619 and M 2013444, and their 16S rRNA sequences were deposited in the GenBank database under Accession Nos. KP162176 and KF640247, respectively. For inoculum preparation, P. putida S-1 was initially incubated in R₂A liquid medium (Sun et al. 2016), and Alcaligenes sp. SY1 was incubated in MM with 50 mg L⁻¹ DMS. Both strains were incubated on a rotary shaker (160 rpm) at 30 °C.

Batch biodegradation experiment

All batch biodegradation experiments were carried out in 250 mL screw-capped Erlenmeyer flasks containing 50 mL of sterile MM with different initial PT and/or DMS concentrations. The bacterial inoculums were obtained at exponential growth phase by centrifugation at 6000 rpm for 10 min at 4 °C, washed with MM twice, and resuspended in MM with an optical density (OD₆₀₀) of 0.1. To ensure the same initial biomass concentration of both strains, 0.94 mL P. putida S-1 suspension and 1 mL Alcaligenes sp. SY1 suspension were introduced. The initial
substrate concentrations were 50 mg L⁻¹ unless otherwise specified, and the introduced volumes of pre-grown cells were consistent with the above-mentioned conditions.

During the degradation experiments, the concentrations of substrates and biomass were determined at regular intervals. The initial concentrations of the substrates kept unchanged in the control experiments without the strains, implying that abiotic loss could be neglected. And all experiments were performed in triplicate.

**Analytical methods**

The residual concentrations of PT and DMS were determined by gas chromatography (Shimadzu GC-14B, JAPAN) equipped with a flame ionization detector and an RTX-1 column (30 m × 0.32 mm × 25 μm, Restek, USA). PT and DMS could be balanced in vapor and aqueous phase in the sealed bottle within 30 min. Then, the aqueous concentrations of substrates were calculated from the measured concentration in the gas phase by using the partition coefficient (Henry’s coefficient). The gas samples (0.8 mL) in the headspace were withdrawn with a gas-tight syringe and injected into the GC to determine the gaseous concentrations of PT and DMS. The temperatures of GC injector, oven, and detector were 200 °C, 80 °C, and 230 °C, respectively. The hydrogen and air flow rates for FID were 40 and 450 mL min⁻¹, respectively.

The CO₂ concentration was determined by gas chromatography (Agilent Technologies, GC 6890 N, USA) equipped with HP-Plot-Q column (30 m × 0.32 mm × 20 μm) and thermal conductivity detector. The carrier gas was helium with a flow rate of 5 mL min⁻¹. The column and detector temperatures were 40 °C and 100 °C, respectively.

The concentration of SO₄²⁻ was determined with the Dionex ICS 2000 ion chromatograph (Thermo Fisher, USA) equipped with IonPac AS19 HC separation column and DS conductance detector. The flow rate of KOH was 1.0 mL min⁻¹, and the column temperature was 30 °C.

The intermediates of PT degradation were identified using a gas chromatograph–mass spectrometer (GC–MS, Agilent 7890N/MS 5975) equipped with an HP-5MS capillary column, as described elsewhere (Chen et al. 2016). Solid-phase extraction with a C18 column was adopted for sample preparation.

Biomass concentrations were monitored by spectrophotometric absorbance at 600 nm (OD₆₀₀) on a spectrophotometer (Hitachi, Tokyo).

**Kinetic modeling**

The description of the degradation kinetics of the substrates (PT and DMS) under different conditions was the main content of modeling. Among the various mathematical models, the pseudo first-order model was most widely applied in many cases (Elango et al. 2011; Boonnarat et al. 2014). It is usually defined as follows:

\[
S_t = S_0 e^{-qt}
\]

where \(q\) is the degradation rate constant of the substrate (h⁻¹), \(S_0\) is the initial aqueous concentration of the substrate, and \(S_t\) is the substrate concentration in the liquid at time \(t\) (the reaction time).

However, substrate interactions caused by the presence of co-substrate would increase the uncertainty in the degradation process. Thus, some of the modified models that can provide an improved fit for the biodegradation process must be considered. In food microbiology, several nonlinear regression functions, such as the Gompertz model, have been widely used in describing the microbial growth or production. Zwietering et al. re-parameterized the Gompertz function through replacing nonsensical mathematical parameters with those of biological meanings to develop the Gompertz Kinetic model, providing a function of the cumulative production \(P\) with time (Eq. 2) (Zwietering et al. 1990).

\[
P(t) = P_{\text{max}} \exp\left(-\exp\left(\frac{R_m}{P_{\text{max}}} (\lambda - t) + 1\right)\right)
\]

where \(P_{\text{max}}\) is the maximum production, \(R_m\) is the maximum rate of production, \(\lambda\) is the lag phase, and \(t\) is the elapsed time. This modified Gompertz kinetic model with the incorporation of parameter \(\lambda\) provides potential for the modeling of biodegradation process with lag.

The new variable cumulative degradation \(D\) and maximum degradation potential \(D_{\text{max}}\) were used in describing substrate consumption as a degradation potential (Eq. 3) (Carvajal et al. 2018). In the present study, the experimental data in the degradation systems with two substrates may be fitted to the modified Gompertz kinetic model.

\[
D(t_0) = D_{\text{max}} \exp\left(-\exp\left(\frac{R_m}{D_{\text{max}}} (\lambda - t) + 1\right)\right)
\]

\[
D(t_0) = \frac{C_0 - C_t}{C_0}
\]

Experimental data were fitted to the models with a nonlinear curve fitting to estimate the kinetic parameters of the models used. For the pseudo-first-order model, substrate concentration vs. time was directly fitted, and the degradation rate constant \(q\) could be obtained. In the modified Gompertz model, the cumulative degradation at \(t\) \((D(t_0))\) was calculated using Eq. (4), where \(C_0\) and \(C_t\) indicate the initial
substrate concentration and substrate concentration as a function of time, respectively.

IstOpt statistical analysis software was used for parameter determination (Zhang et al. 2013). Levenberg–Marquardt and universal global optimization algorithms were used for calculating the correlation coefficient ($R^2$).

**Results and discussion**

**Long lag occurred in DMS degradation in binary mixture**

Figure 1 showed the individual and simultaneous biodegradation performance of 50 mg L$^{-1}$ PT and 50 mg L$^{-1}$ DMS by *P. putida* S-1 and *Alcaligenes* sp. SY1. The cell growth was also recorded. It could be observed that PT was almost completely degraded in 33 h without lag phase, regardless of the presence of DMS. This indicated that the degradation of PT was not affected by the presence of DMS. By contrast, it was not until 81 h later that DMS began to be biodegraded in the presence of PT. And a lag of approx. 10 h was observed when PT was absent (Fig. 1a). Similar phenomenon in double-substrate system was also previously reported (Chen et al. 2007; Hsieh et al. 2008). The total biomass concentration expressed in OD$_{600}$ increased with the degradation of PT, and then the growth ceased and remained for a long time until the degradation of DMS started (Fig. 1b). Similar diauxic-growth phenomena had also been reported in previous studies, when bacteria switched between electron donors (Monod 1949; Lisbon et al. 2002). Notably, biomass continued to increase, even after PT was completely degraded, whereas DMS degradation was surprisingly far from starting. Besides, the concentrations of CO$_2$ and SO$_4^{2−}$ kept on increasing when PT was completely depleted (Fig. 1b), which was probably ascribed to the further mineralization of the metabolic intermediates of PT.

Subsequently, the influence of the substance concentration on the degradation of PT and DMS was investigated. As shown in Table 1, when the concentration of DMS was fixed at 50 mg L$^{-1}$, and the concentration of PT was varied at 0, 10, 20, 50, and 100 mg L$^{-1}$, a lag of 11–117 h was observed before the onset of DMS degradation, and the lag duration was extended with the increase of PT concentration. When

| Initial PT (mg/L) | Initial DMS (mg/L) | Time for 90% PT removal (h) | Lag to DMS degradation (h) | Time for 90% DMS removal (h) | OD$_{600}$ when 90% PT removed | OD$_{600}$ when 90% DMS removed |
|-------------------|-------------------|---------------------------|--------------------------|--------------------------|-------------------------------|-------------------------------|
| 0                 | 50                | /                         | 11                       | 45                       | /                             | 0.075                         |
| 10                | 50                | 8                         | 33                       | 57                       | 0.018                         | 0.080                         |
| 20                | 50                | 11                        | 57                       | 93                       | 0.037                         | 0.96                          |
| 50                | 50                | 21                        | 81                       | 129                      | 0.051                         | 0.108                         |
| 100               | 50                | 28                        | 117                      | 153                      | 0.085                         | 0.148                         |
the concentration of PT in the dual-substrate mixture was 100 mg L\(^{-1}\), its degradation efficiency could reach 90% in 28 h; however, the lag phase for DMS degradation was as long as 117 h. The actual degradation time required for 90% DMS removal was also influenced, ranging from 24 to 48 h. When the PT concentration was 10 mg L\(^{-1}\), 90% DMS could be degraded in 24 h, which was even shorter than that without PT (34 h). By contrast, when the initial PT concentration increased to 50 mg L\(^{-1}\), the actual degradation time for 90% DMS removal prolonged to 48 h. Thus, it could be concluded that PT concentration could affect the degradation rate of DMS when the lag was not considered.

The cause of the long DMS-degrading lag

To find out the cause of such lag-related inhibition, several control experiments were conducted.

Firstly, the degradation performance of DMS in presence of sole Alcaligenes sp. SY1 and both strains were investigated. As displayed in Fig. 2, the degradation efficiencies in both cases were very analogous. DMS was biodegraded completely in 60 h, which indicated that DMS could not be degraded by P. putida S-1, and the presence of P. putida S-1 was not the cause of the lag phase during DMS degradation.

When PT was present in the medium without P. putida S-1, DMS could not be degraded by Alcaligenes sp. SY1. This suggested that PT itself may cast a detrimental effect on DMS degradation. To test this possibility, Alcaligenes sp. SY1 strains were exposed to 50 mg L\(^{-1}\) PT for 24, 48, and 72 h, then the cells were collected by centrifugation, washed, and resuspended for DMS degradation in fresh MM. As shown in Fig. 3, lag lasted approx. 90, 110, and 140 h, respectively, and the longer the times exposed to PT, the longer the lag phase would be. And the lag durations were even longer than that observed in Fig. 1b, which was consistent with the results in Table 1. Therefore, it could be concluded that the concentration of PT and the exposure time of Alcaligenes sp. SY1 to PT are concerned with the lag duration of DMS metabolism in the mixture.

Besides, it has been widely reported that the formation and accumulation of intermediates of one substrate can cast inhibitory influence on the degradation of another (Hazarati et al. 2015; Reardon et al. 2015). Since DMS could be degraded after a long lag duration when PT and its degrader P. putida S-1 were co-present, it may suggest that Alcaligenes sp. SY1 could survive from the possible soluble antagonistic compounds secreted by P. putida S-1, or the concentration of antagonistic compounds was relatively low to completely kill Alcaligenes sp. SY1. Then, the components and concentrations of the intermediates were detected, when PT was completely degraded by P. putida S-1 (at 32 h of the whole process). The results showed that PT could be degraded into dipropyl disulfide, 3-hexanol, 2-hexanol, 3-hexanone, and 2-hexanone, and their accumulated concentrations in the solutions were all lower than 5 mg L\(^{-1}\) (see Table 2). And as the degradation time extended, such intermediates could be further degraded, resulting in the concentrations being less than 0.1 mg L\(^{-1}\) after 58-h degradation. Moreover, the variation trend of DMS degradation was almost identical with that of the control group except for the lag, namely when PT was completely depleted, intermediates...
were remained, and the biomass of \( P. \text{ putida} \) S-1 was withdrawn from the liquid. Furthermore, it was found that the addition of every intermediates of PT with a concentration of 5 mg L\(^{-1}\) did not increase the lag phase of DMS degradation (data not shown). All these results robustly proved that \( Alcaligenes \) sp. SY1 could only live by DMS, and the metabolites of PT degraded by \( P. \text{ putida} \) S-1 were not concerned with the DMS-degrading lag.

**Citric acid acted as an effective “lag reductor”**

It is of great importance to shorten the lag phase of DMS degradation in a dual-substrate solution. Adding extra carbon sources can probably enhance the degradation rate of pollutants (Mukherjee and Bordoloi 2012). Some readily metabolized organic substrates, such as yeast extract, tryptone, and glucose, might stimulate biomass growth, thereby improving the mineralization of recalcitrant organic compounds (Chen et al. 2009; Ziagova and Liakopoulou-Kyriakides 2007). It was also reported that benzene degradation could greatly enhanced by tetrahydrofuran, which could act as an “energy generator” (Yang et al., 2011). Therefore, to reduce the lag phase for DMS degradation, various organic substrates, like yeast extract, tryptone, methanol, starch, acetone, and sucrose, were tentatively added and their influence on DMS degradation was investigated and compared. As shown in Fig. 4a, glucose, yeast extract, and citric acid were all beneficial for the removal of DMS when PT coexisted. And the addition of these three carbon sources exhibited varying reduction for the lag phase. The effect of citric acid on the decrease of the lag phase demonstrated to be the most remarkable; only 24 h of lag phase was observed before the onset of DMS degradation. Nevertheless, the DMS biodegradation rates after lag phase under different conditions were similar with each other, regardless of the presence and kinds of the supplements. However, the cause behind the superior effect of citric acid on lag reduction was complex and remained unknown.

The addition of extra carbon sources could also enhance the biodegradation of PT, as shown in Fig. 4b, which may shorten the exposure time of \( Alcaligenes \) sp. SY1 to PT and thus reducing the lag phase for DMS degradation. However, the stimulation effect toward PT degradation upon the addition of citric acid was not better than those upon glucose and yeast extract. As an easily metabolized organic substrate,
citric acid could also provide additional energy for DMS degradation, analogous to that of glucose and yeast extract. Besides, it is the main substrate in Kreb’s cycle and hence probably producing energy more easily. Moreover, Mahmud et al. found that citric acid could enhance the tolerance of *Brassica juncea* to cadmium toxicity through upregulating the antioxidant defense and glyoxalase systems (Al Mahmud et al. 2018), thus we speculated that citric acid may also improve the tolerance of *Alcaligenes* sp. SY1 to PT toxicity.

**Kinetics of PT and DMS biodegradation under single and binary substrate conditions**

Pseudo-first-order model was first used to describe the biodegradation of substrates. The fitness of the first-order model for PT degradation in the dual-substrate biodegradation tests was analogous to that obtained under the single-substrate condition (see Tables 3 and 4). The $R^2$ values obtained for PT degradation at lower concentrations (0.931 and 0.926) were relatively higher than that obtained at higher concentrations (0.892 and 0.895). Under the dual-substrate condition, when the PT concentration exceeded 10 mg L$^{-1}$, the model provided poor fitting results ($R^2 < 0.9$). As shown in Fig. 5, when PT biodegradation was fitted with logarithmic mode, the fitting curves matched well with the experimental results in the first few hours, but it was then gradually deviated as the biodegradation proceeded. When the initial PT concentrations were 10, 20, 50, and 100 mg L$^{-1}$, the degradation rate constants ($q$) obtained for PT degradation under the single-substrate condition were 0.16, 0.09, 0.04, and 0.03 h$^{-1}$, respectively. A negative correlation was found between $q$ and PT concentration. The $q$ obtained at every PT concentration under the dual-substrate condition was slightly higher, which indicated that the presence of DMS could slightly enhance the degradation of PT.

Unfortunately, the pseudo-first-order model failed to predict the kinetics of DMS biodegradation under the dual-substrate condition. When PT and its degrader *P. putida* S-1 were co-present in the medium, the lag phase accounted for more than 50% of the whole time of DMS degradation. Such lag phase made the modeling of the DMS degradation process difficult to be described.
Therefore, the Monod model was adopted for the description of microbial growth after the lag phase was excluded (Strigul et al. 2009). Meanwhile, because the lag phase mattered the completion of pollutant elimination, it also needed to be predicted. Nevertheless, conventional mathematical models, such as the first-order model, Andrews model, and SKIP model, which account for the inhibition effect between dual substrates, failing to well fit the experimental data in this study. Encouragingly, Christen et al. used the Gompertz model to calculate the maximum degradation rate of phenol, and the results were well fitted \( (R^2 > 0.98) \) (Christen et al. 2012). Inspired by this, the Gompertz model was then adopted and modified by incorporating \( \lambda \) as the lag phase, to describe the biodegradation of DMS (Fig. 6), and the corresponding kinetics parameters were estimated. As displayed in Table 5, the \( R^2 \) was higher than 0.97, and the maximum degradation potential \( (D_{\text{max}}) \) reached 1.00, confirming the thorough degradation of PT and DMS in the whole degradation process. The obtained lag phase parameters \( (\lambda) \) for DMS degradation were 16.19, 35.59, 69.38, 90.46, and 117.08 h, when mixed with PT at initial concentrations of 0, 10, 20, 50, and 100 mg L\(^{-1}\), respectively. All these values were in good accordance with the experimental results of DMS degradation (see Table 1).

**Table 5** Kinetics parameters estimated with the modified Gompertz model for the degradation of 50 mg L\(^{-1}\) DMS in the dual-substrate solution with different initial PT concentrations

| PT concentration (mg/L) | \( D_{\text{max}} \) (mg/mg) | \( R_m \) (mg/(mg h)) | \( \lambda \) (h) | \( R^2 \) |
|-------------------------|-----------------------------|-----------------------|-----------------|--------|
| 0                       | 1.00                        | 0.13                  | 16.19           | 0.988  |
| 10                      | 1.00                        | 0.17                  | 36.59           | 0.996  |
| 20                      | 1.00                        | 0.13                  | 69.38           | 0.990  |
| 50                      | 1.00                        | 0.07                  | 90.46           | 0.992  |
| 100                     | 1.00                        | 0.09                  | 117.08          | 0.993  |

**Fig. 6** Time courses of the cumulative degradation of 50 mg L\(^{-1}\) DMS and different concentrations of PT (a: 10 mg L\(^{-1}\) PT; b: 20 mg L\(^{-1}\) PT; c: 50 mg L\(^{-1}\) PT; d: 100 mg L\(^{-1}\) PT). Symbols represent experimental data [PT (●), DMS (■)], whereas the lines represent Gompertz model fitting.
The modified Gompertz model was further used to describe the degradation of PT at different initial concentrations under single-substrate condition. The \( \lambda \) values were estimated to be 2.32, 4.20, 5.88, and 6.44 h at concentrations of 10, 20, 50, and 100 mg L\(^{-1} \), which was barely detected through experiments. The correlations between \( \lambda \) and PT concentration were consistent with that reported in previous studies, i.e., the lag phase increased with the initial substrate concentration (Juang and Tsai 2006; Christen et al. 2012), indicative of the applicability of the modified Gompertz model in estimating the lag phase of substrate degradation. Compared with those in single-substrate solution, the \( \lambda \) values of PT degradation were relatively lower and the maximum degradation rates \( R_m \) were relatively higher in dual-substrate conditions, when the initial DMS concentration was < 50 mg L\(^{-1} \) (Table 4), which indicated low-concentration DMS could promote the degradation of PT, probably attributing to the metabolism of the degrading intermediates of PT by Alcaligenes sp. SY1. However, when the initial DMS concentration was > 50 mg L\(^{-1} \), the \( R_m \) was slightly lower (0.12), indicative of a mild inhibitory effect on PT degradation, which may be ascribed to the competition for the limited mineral elements between the two bacteria.

The calculated \( R_m \) value for DMS biodegradation in the presence of PT with different initial concentrations was displayed in Table 5. When the concentration of PT was 10 mg L\(^{-1} \), the \( R_m \) was 0.17 mg mg\(^{-1} \) h\(^{-1} \), slightly higher than that without PT addition (0.13 mg mg\(^{-1} \) h\(^{-1} \)). It could thus be inferred that, if PT-triggered lag was not considered, a slight enhancement for DMS biodegradation after PT addition could be achieved at a low PT concentration (Chen et al. 2016). This was the first study reported that only lag prolongation, rather than degradation rate reduction, accounted for the biodegradation inhibition of one pollutant by the other in a binary mixture. However, a concentration of PT higher than 20 mg L\(^{-1} \) could lead to lower \( R_m \), and the \( R_m \) decreased with the increasing of PT concentration. Two probable reasons may account for such results. One was the competition for the limited mineral elements between Alcaligenes sp. SY1 and P. putida S-1; the other was the inhibition of high-concentration PT to the enzyme activity responsible for DMS biodegradation.

**Conclusion**

In this study, simultaneous biodegradation of malodorous PT and DMS with P. putida S-1 and Alcaligenes sp. SY1 was investigated and related interactions were explored. PT was completely degraded in 33 h, while a lag of 10 h was observed for DMS degradation, and the lag was even extended to 81 h in the mixture. Careful analysis found that the lag was mainly attributed to the exposure of DMS degrader (Alcaligenes sp. SY1) to PT, rather than the PT metabolites and PT degrader. And the exposure time and PT concentration largely influenced the lag duration. Citric acid could serve as an effective “lag reductor,” decreasing the lag to 24 h. Pseudo-first-order model was suitable for the description of PT degradation, but failed to predict the kinetics of DMS biodegradation. A modified Gompertz model incorporated the lag phase parameter \( \lambda \) was developed for the successful description of PT and DMS degradation kinetics in the dual-substrate conditions, which revealed that the effect of PT on DMS degradation depended on the initial concentration of PT and vice versa. When the concentration of DMS was < 50 mg L\(^{-1} \), the biodegradation of PT could be promoted, while a higher concentration would cast an inhibitory effect on PT degradation. And if the PT-triggered lag was not considered, low-concentration PT could promote the biodegradation of DMS, while a higher concentration (> 20 mg L\(^{-1} \)) could cast a negative effect. It is believed that the mechanism proposed in this work may inspire more rational operation to obtain superior simultaneous removal efficiency of multiple gaseous pollutants coexisted in practical situations.

**Acknowledgements** This work was financially supported by the National Natural Science Foundation of China (NSFC-51778581, NSFC-52070169).

**Availability of data and materials** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Author contribution** QL was a major contributor in investigation, paper writing and revision; ZT performed the experiments and data analysis; JZ participated in the completion of the experiments; JH participated in the data analysis; JC contributed to the resources and funding; DC made an important contribution to the resources, funding, and supervision. All authors have read and approved the final manuscript.

**Funding** This work was financially supported by the National Natural Science Foundation of China (NSFC-51778581, NSFC-52070169).

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**References**

AI Mahmoud J, Hasanuzzaman M, Nahar K, Bhuyan MHMB, Fujita M (2018) Insights into citric acid-induced cadmium tolerance and phyto remediation in Brassica juncea L.: Coordinated functions of metal chelation, antioxidant defense and glyoxalase systems. Ecotoxicol Environ Safety 147:990–1001

Bielefeldt AR, Cort T (2005) Dual substrate biodegradation of a non-ionic surfactant and pentachlorophenol by Sphingomonas chlorophenolica RA2. Biotechnol Bioeng 89:680–689

Boonmorat J, Chiemchaisri C, Chiemchaisri W, Yamamoto K (2014) Removals of phenolic compounds and phthalic acid esters in
landfill leachate by microbial sludge of two-stage membrane bio-reactor. J Hazard Mater 277:93–101
Carvajal A, Akmira I, Navia D, Perea R, Munoz R, Lebrero R (2018) Anoxic denitrification of BTEx: Biodegradation kinetics and pollutant interactions. J Environ Manag 214:125–136
Chen DZ, Chen JM, Zhong WH (2009) Enhancement of methyl tert-butyl ether degradation by the addition of readily metabolizable organic substrates. J Hazard Mater 167:860–865
Chen DZ, Ding YF, Zhou YY, Ye JX, Chen JM (2014) Biodegradation kinetics of tetrahydrofuran, benzene, toluene, and ethylbenzene as multi-substrate by Pseudomonas oleovorans DT4. Int J Environ Res Pub Health 12:371–384
Chen DZ, Sun YM, Han LM, Chen J, Ye JX, Chen JM (2016) A newly isolated Pseudomonas putida S-1 strain for batch-mode-propanethiol degradation and continuous treatment of propanethiol-containing waste gas. J Hazard Mater 302:232–240
Chen DZ, Zhao XY, Miao XP, Chen J, Ye JX, Chen ZW, Zhang SH, Chen JM (2018) A solid composite microbial inoculant for the simultaneous removal of volatile organic sulfide compounds: preparation, characterization, and its bioaugmentation of a biotrickling filter. J Hazard Mater 342:589–596
Chen YM, Lin TF, Huang C, Lin JC (2008) Cometabolic degradation kinetics of TCE and phenol by Pseudomonas putida. Chemosphere 72:1671–1680
Chen YM, Lin TF, Huang C, Lin JC, Hsieh FM (2007) Degradation of phenol and TCE using suspended and chitosan-bead immobilized Pseudomonas putida. J Hazard Mater 148:660–670
Chignell JF, Park S, Lacerda CMR, De Long SK, Reardon LF (2018) Label-free proteomics of a defined, binary co-culture reveals diversity of competitive responses between members of a model soil microbial system. Microbial Ecology 75:701–719
Christen P, Vega A, Casalot L, Simon G, Auria R (2012) Kinetics of aerobic phenol biodegradation by the acidophilic and hyperthermophilic archaean Sulfolobus solfataricus 98/2. Biochem Eng J 62:56–61
Van Durme J, Dewulf J, Leys C, Van Langenhove H (2008) Combining non-thermal plasma with heterogeneous catalysis in waste gas treatment: A review. Appl Catal B: Environ 78:324–333
Elango V, Kurtz HD, Freedman DL (2011) Aerobic cometabolism of trichloroethene and cis-dichloroethene with benzene and chlorinated benzenes as growth substrates. Chemosphere 84:247–253
Giri BS, Kim KH, Pandey RA, Cho J, Song H, Kim YS (2014) Review of biotreatment techniques for volatile sulfur compounds with an emphasis on dimethyl sulfide. Process Biochemistry 49:1543–1554
Giri BS, Pandey RA (2013) Biological treatment of gaseous emissions containing dimethyl sulfide generated from pulp and paper industry. Bioresource Technology 142:420–427
Han B, Liu YT, Jian Hui W, Feng YC (2018) Characterization of industrial odor sources in Binhai New Area of Tianjin, China. Environ Sci Pollut Res Int 25:14006–14017
Hazrati H, Shayegan J, Seyedi SM (2015) Biodegradation kinetics and interactions of styrene and ethylbenzene as single and dual substrates for a mixed bacterial culture. J Environ Health Sci Eng 13:1–12
Hsieh FM, Huang C, Lin TF, Chen YM, Lin JC (2008) Study of sodium tripolyphosphate-crosslinked chitosan beads entrapped with Pseudomonas putida for phenol degradation. Process Biochemistry 43:83–92
Jo WK, Shin MH (2010) Applicability of a continuous-flow system inner-coated with S-doped titania for the photocatalysis of dimethyl sulfide at low concentrations. Journal of Environmental Management 91:2059–2065
Juang RS, Tsai SY (2006) Growth kinetics of Pseudomonas putida in the biodegradation of single and mixed phenol and sodium salicylate. Biochem Eng J 31:133–140
Kennes C, Veiga MC (2013) Air pollution prevention and control: bioreactors and bioenergy (John Wiley & Sons, Ltd.).
Li H, Mihelcic JR, Crittenden JC, Anderson KA (2003) Field measurements and modeling of two-stage biofilter that treats odorous sulfur air emissions. J Environ Eng 129:684–692
Lisbon K, McKeane M, Shekar S, Svoronos SA, Koopman B (2002) Effect of dissolved oxygen onoxic/anoxic diauxic lag of P. denitrificans. J Environ Eng 128:391–394
Monod J (1949) The Growth of Bacterial Cultures. Ann Rev Microbiol 3:371–394
Mukherjee AK, Bordoloi NK (2012) Biodegradation of benzene, toluene, and xylene (BTX) in liquid culture and in soil by Bacillus subtilis and Pseudomonas aeruginosa strains and a formulated bacterial consortium. Environ Sci Pollut Res 19:3380–3388
Padhi SK, Gokhale S (2017) Treatment of gaseous volatile organic compounds using a rotating biological filter. Bioresource Technology 244:270–280
Pala-Ozkok I, Rehman A, Yagci N, Ubay-Cokgor E, Jonas D, Orhon D (2012) Characteristics of mixed microbial culture at different sludge ages: Effect on variable kinetics for substrate utilization. Bioresource Technology 126:274–282
Qiu X, Deshusses MA (2017) Performance of a monolith biotrickling filter treating high concentrations of H2S from mimic biogas and elemental sulfur plugging control using pigging. Chemosphere 186:790–797
Ras MR, Borrull F, Marcé RM (2008) Determination of volatile organic sulfur compounds in the air at sewage management areas by thermal desorption and gas chromatography-mass spectrometry. Talanta 74:562–569
Reardon LF, Mosteller DC, Bull JD, Rogers. (2015) Biodegradation kinetics of benzene, toluene, and phenol as single and mixed substrates for Pseudomonas putida F1. Biotechnol Bioeng 69:385–400
Strigul N, Dette H, Melas VB (2009) A practical guide for optimal designs of experiments in the Monod model. Environ Modell Softw 24:1019–1026
Sun YM, Qiu JG, Chen DZ, Ye JX, Chen JM (2016) Characterization of the novel dimethyl sulfide-degrading bacterium Alcaligenes sp. SY1 and its biochemical degradation pathway. J Hazard Mater 304:543–552
Wani AH, Lau AK, Brionion RMR (1999) Biofiltration control of pulping odors – hydrogen sulfide: performance, macrokinetics and coexistence effects of organo-sulfur species. J Chem Technol Biotechnol 74:9–16
Zhang HJ, Liu JT, Cao YJ, Wang YT (2013) Effects of particle size on lignite reverse flotation kinetics in the presence of sodium chloride. Powder Technology 246:658–663
Zhang XY, Gao B, Creamer AE, Cao CC, Li YC (2017) Adsorption of VOCs onto engineered carbon materials: a review. J Hazard Mater 338:102–123
Yang ZY, Chen DZ, Zhu RY, Chen JM (2011) Substrate interactions during the biodegradation of BTEx and THF mixtures by Pseudomonas oleovorans DT4. Bioresearch Technology 102:6644–6649
Yang ZY, Huang HL, Shen DS (2016) Multi-substrate biodegradation interaction of 1, 4-dioxane and BTEx mixtures by Acinetobacter baumannii DD1. Biodegradation 27:1–10
Ziagova M, Liakopoulou-Kyriakides M (2007) Kinetics of 2,4-dichlorophenol and 4-Ch-Im-cresol degradation by Pseudomonas sp. cultures in the presence of glucose. Chemosphere 68:921–927
Zwijerhing MH, Jongenburger I, Rombouts FM, Van’T Riet K (1990) Modeling of the bacterial growth curve. Appl Environ Microbiol 56:1875–1881

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.