Bioaugmentation mitigates ammonia and hydrogen sulfide emissions during the mixture compost of dewatered sewage sludge and reed straw

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Abstract
This study investigated the effectiveness of bio-augmenting aerobic cell culture to mitigate ammonia and hydrogen sulfide emission in sewage sludge composting amended with reed straw (with the weight ratio of 1:0.3–0.4). During the 20-day aerated lab-scale composting, adding 200-mL culture (56.80 NTU) reduced ammonia and hydrogen sulfide emissions by 38.00% and 54.32%, and conserved total nitrogen and sulfate by 39.42% and 70.75%, respectively. Organic matters degradation was quick started 1 day ahead. Comparing to the control, nitrate content increased 38.75% at the end of the compost. Bioaugmentation evened the distributions of bacterial communities in the thermophilic phase. The shift was mainly due to 22.97% of relative abundance of Proteobacteria depressed and 157.16% of Bacteroidetes increased, which were beneficial for nitrogen conservation and glycan breakdown, respectively. In summary, the results demonstrated that bioaugmentation addition could be an effective strategy for enhanced sludge composting.

Keywords Sewage sludge · Bioaugmentation · Compost · nitrogen loss · Hydrogen sulfide emission · Bacterial succession

Introduction
Dewatered sewage sludge (DSS) was generated during the treatment of domestic sewage in wastewater treatment plants (WWTP) and was identified as biosolids. Composting was an economical and environmentally favorable technology for DSS stabilization and resource utilization, and has become more important for decomposing organic wastes than before (Doloman et al. 2020; He et al. 2018; Li et al. 2017).

The composting process involved complex physical-chemical interactions between the organic matter (OM) and the decomposer. The decomposition of organic matter could be accelerated by a mixed population of microorganisms in a warm and moist environment (Wang and Liang 2021; Costa et al. 2021; Negi et al. 2020). Some organic matters were mineralized to carbon dioxide (CO₂), ammonia (NH₃), and water, and others were transformed to nutrient-rich, humus-like materials (Yaman 2020; Shou et al. 2019; Doloman et al. 2020; Du et al. 2019).

However, an inevitable problem in DSS compost was odor emission, especially that of NH₃ and H₂S, which correspondingly caused nitrogen and sulfur loss. Ammonia release accounted for up to 80% of nitrogen loss during organic waste composting (Shou et al. 2019; Meng et al. 2016; Toledo et al. 2018). Sulfur deficiency in crop production was described to be a major problem in most parts of the world (Grant et al. 2012). The recovery of nitrogen and sulfur from the composting process could help to compensate for these shortages and could also increase its value as a synthetic fertilizer substitute (Becarelli et al. 2019; Shou et al. 2019; Li and Li 2015).

Odor emission was mainly resulting from the high moisture content, the low carbon-to-nitrogen (C/N) ratio of DSS and low air-filled porosity along with the poor permeability (Yaman 2020; Doloman et al. 2020; Shou et al. 2019). The average specific heat capacities (calorific value) of DSS in China was about 11.850 MJ/kg, 22.4–37.7% lower than that in the developed countries (Cai et al. 2010). Most agricultural and forest residues, such as annual herbage, cotton
gin waste, rice straw, and cornstalks, had higher calorific values from 12.18 to 18.06 MJ/kg (Cai et al. 2010; He et al. 2007). Those carbonaceous and lignocellulosic bulking agents were commonly adopted to reduce the energy required to increase the pile temperature, optimize the composting condition for improved quality of the compost product, and reduce odor emission (Shao and Zheng 2014; Shou et al. 2019; Shou et al. 2017).

Another dimension was the complex structures of organic matters, which was the main bottlenecks in the biodegradation and conversion in DSS compost. In China, DSS contained about 60–70% of organic matters, including 62% of stable sludge cells, 8–15% of cellulose, and 10.2% humus (Dai et al. 2016; Xu et al. 2018). That signified a long start-up time of sludge composting or the lag phase with low OM degradation efficiency, often relating with the nitrogen and sulfur loss and odor emission (Becarelli et al. 2019; Borowski et al. 2017; Quan et al. 2017). Therefore, bioaugmentation, the introduction of pre-grown robust consortium with specific catabolic abilities into the system, could be performed and may be advantageous.

Bioaugmentation had been established as an economical, ecological, and environmental friend treatment to manipulate the microbial composition and accelerate related bio-metabolism (Costa et al. 2021; Poorsoleiman et al. 2020; Zhao et al. 2019; Doloman et al. 2020). It was capable of improving the removal of the contaminants in natural and environmental systems by circumventing insufficient response time and initiating the removal with a minimal lag phase (Wang and Liang 2021; McGenity et al. 2017). Success of bioaugmentation was only possible if there was a substrate-specific niche available for the microbe to be incorporated into the already densely established consortia (Shao and Zheng 2014; Doloman et al. 2020). Therefore, the special consortium could be isolated and enriched from sludge, mainly to effectively improve the conditioning of wastewater sludge, such as accelerating the hydrolysis by attacking the sludge flocs, enhancing the start-up of a bioreactor, and shortening the reaction time (Poorsoleiman et al. 2020; Xin et al. 2017; McGenity et al. 2017). Those microbial consortia in the system could be driven by the preponderant environmental factors to get to a relative balance level (Zhao et al. 2019; Xin et al. 2017).

In this study, two composting batch trials were conducted with and without bioaugmentation, and the objectives were to (1) illustrate the changes of OM degradation and the mitigation of NH3 and H2S emission enhanced by bioaugmentation, and (2) dissect the shifting behaviors of bacterial community composition for the interactions of external culture with host bacteria. The outcomes were expected to put forward bioaugmentation to be a more practical alternative strategy in odor emission elimination and quick start of DSS compost.

## Materials and methods

### Compost materials

DSS was obtained from the local municipal wastewater treatment plant, and reed straw was from the local wetland. Reed straw was sieved through a 1-mm mesh and was used as the bulking agent. The main characteristics of both initial materials are shown in Table 1. Aerobic indigenous bacteria with less NH3 and H2S emission and grown faster were isolated from the sludge using plate separation method. The optimum growth temperature of the consortia was 45 °C and the turbidity reached the highest in 21 h. The culture was dilated with phosphate buffering solution (pH= 6.61) and the turbidity in nephelometric turbidity units (NTU) was 56.8.

### Composting experiment setup

Compost mixture consisted of DSS and reed straw with the weight ratio of 1:0.3–0.4 and the moisture content was about 65%. Two identical lab-scale reactors were performed under the same condition throughout the experiment, one marked as “bio-augmented” with 200 mL of cell culture and another marked as “control” with 200 mL of deionized water. The main characteristics of the experimental materials are also listed in Table 1. The reactors had 10-L effective volume, with a height of 270 mm and an inner diameter of 245 mm.

The 20-day composting process was divided into three phases based on the temperature control of the reactors: the initial calefactive at room temperature (day 0–2), the thermophilic phase with external heating from 50 °C hot water (day 3–12), and the maturation phase with no external heating until day 20. Aeration apparatus adopted in both runs was the patented product of our team and the patent number was ZL 2019 2 20489343.3. Continuous airflow rate was 0.3 L/min. The exhausted gas was introduced into NaOH (2 M) and H2SO4 (1 M) solution for CO2 and NH3 absorption, respectively. There was no leachate in the two systems. Pile turning was provided every other day.

| Table 1  | Main characteristics of materials used in the compost |
|-------|-----------------------------------|
|        | pH  | ω (%) | OM (%) | TN (mg/g) | SO4− (mg/g) |
| DSS    | 6.65| 83.73 | 66.57  | 57.10     | 3.11        |
| Reed straw | 5.77| 5.35  | 88.36  | 9.78      | 9.46        |
| Control | 6.39| 67.87 | 83.16  | 21.37     | 6.22        |
| Bio-augmented | 6.36| 66.95 | 82.82  | 21.19     | 6.05        |
Sampling and analysis

Samples were collected from the two reactors according to the quartering method and scheduled on days 0, 2, 4, 6, 8, 10, 14, and 20. Each sample was stored at 4 °C immediately for the determination of physical and chemical parameters. Sub-samples collected on day 2 (initial phase), day 6 (thermophilic phase), and day 20 (maturation phase) were stored at −20 °C for DNA extraction and sequencing.

The moisture content of composting materials (ω) was determined by drying the samples at 105 °C for 2 h, and organic matter (OM) by measuring the loss of dry-solid mass after ignition at 550 °C in a muffle furnace for 1 h. The value of pH was measured at a ratio of 1:5 (wet weight of composting sample: volume of deionized water) after shaking equilibration for approximately 4 h using a pH meter (E-201-C, Lei-ci, Shanghai, China). Water-soluble sulfate was deposited with Barium chloride and then detected with gravimetric method (MEE 2012). TN measurement was carried out following the methods of digestion with alkaline Potassium persulfate and detected with UV spectrophotometry (MOHURD 2005). NH₄⁺-N, NO₂⁻-N, and NO₃⁻-N were extracted with potassium chloride (1 mol/L) and determined by phenol sodium-sodium hypochlorite colorimetry, phenol disulfonyl acid colorimetry, and Gerry reagent colorimetry, respectively (Belyaeva and Haynes 2009).

NH₃ emissions were quantified with titration method (Liu et al. 2011), and H₂S concentration online was detected with portable H₂S detector with the range of 0–20 ppm (LB-MS4X, Lubo, Qingdao, Shandong Province, China). The amount of NH₃ and H₂S production was determined daily and the compost temperature was monitored and recorded once a day. When the emissions of ammonia and H₂S were under the detection limit, 0.36 mg/day of NH₃ and 0.12 mg/day of H₂S, half of the least concentrations detected during the compost, were adopted every day.

Bacterial DNA extraction and sequencing

Bacterial genomic DNA was extracted from the sample using the MO BIO PowerSoil® DNA Isolation Kit. Fusion primer was adopted and the sequences were designed as follows:

F 5’-AATGATACGGCGACCACCGAGATCTACAG-3’; R 5’-CAAGCAGAATGGTCACACTATAG-3’;
TCTTTCCCTACACGACGCTCTTCCGATCT- barcode F1- universal -3’; R 5’-CAAGCAGAATGGTCACACTATAG-3’;
TCTTTCCCTACACGACGCTCTTCCGATCT- barcode R2, GTGACTACCTGGTACCGACGCTCTTCCGATCT- barcode
TCTTTCCCTACACGACGCTCTTCCGATCT- barcode R1- universal -3’.

Universal primer (bacterial 16S V4–V5) was adopted and the sequences were the following:

515F 5’-GTGCCAGCMGCAGCGGTAA-3’, 926R 5’- CCGTCAATTCMTTGTAGTTT-3’.

AxyPrep DNA gel recovery kit recovery and real-time fluorescence quantity with the FTC-3000™ real-time PCR instrument were used to purify and quantity PCR product. The purified samples were for the sequencing of bacterial diversity using Illumina NGS (Tinygene Biotechnology Co., Ltd., Shanghai, China) (www.tinygene.com). Operational taxonomic units (OTUs) were identified identically at a 97% sequence homology, and the dilution curve was drawn for the optimized OTUs.

Statistical analysis

Organic matter loss and gas emission in the compost

As a microbial-mediated process, OM loss (OML) and gas emission could be described by a first-order kinetic model. The rate of OM mineralization and the production profiles of cumulative NH₃ and H₂S reflected the nature of the exponential growth curve (Negi et al. 2020). OML and the cumulative yield of gas were calculated as the following (Paredes et al. 2001; Bernal et al. 1996; Santos et al. 2011b; Negi et al. 2020):

\[
OML = A \left(1 - e^{-k_1 t}\right)
\]

\[
Y = Y_{\text{max}} \left(1 - e^{-k_2 t}\right)
\]

where \(A\) reflected the potentially mineralizable OM, \(k_1\) and \(k_2\) were the rate constants (day⁻¹), \(Y_{\text{max}}\) was the maximum yield of gas (mg), and \(Y\) was cumulative yield of gas (mg) at sample time \(t\) (day). Because of the less biochemical metabolism at the start-up period in the present study, “t” calculated began on the 2.5th day for NH₃ and the 0.6th day for H₂S in this study.

Indexes of bacterial community diversity, evenness, and similarity

In order to evaluate the bacterial community shifts in the piles, Shannon index (\(H\)) (Shannon 1948; Eichner et al. 1999) and equitability index (\(E\)) (Stamper et al. 2003) were applied to demonstrate the diversity and the evenness of bacterial community (Xin et al. 2015).

\[
H = \sum p_i \ln p_i
\]

\[
E = \frac{H}{\ln S}
\]

where \(p_i\) was the relative abundance of the species \(i\) and \(S\) was the number of the OTUs.

Data analysis

Experimental data were compared using analysis of paired Student’s \(T\) test (\(T\) test) at a 95% confidence level (\(p < \)
Results and discussion

Temperature, pH, and degradation of organic matters profiles

In both piles, parameters of temperature, pH, and degradation of organic matters showed a similar pattern along the process (Fig. 1).

Temperature variations during composting were the result of the thermal balance between the heat generated from the biodegradation of organic matters and the heat loss through convection, evaporation, and radiation (Wang and Liang 2021; Costa et al. 2021; Becarelli et al. 2019). The temperature of the bio-augmented pile was higher than the control (Fig. 1a). Energy (kJ) emitted from the bioaugmentation mass was the product of the mass of compost (kg), the heat capacity of the compost (kJ/kg/K), and the increase of temperature of the composting mass (K) (Santos et al. 2016a, 2016b). The mean of the energy produced in the bio-augmented mass was 9908.60 MJ/day more than that in the control.

The parameter of pH was common and vital to mediate the microbial multi-functional metabolization (Negi et al. 2020; Shou et al. 2019). The mean pH value of the control pile was 7.26± 0.78, higher than 6.87± 0.46 of the bio-augmented (p< 0.05) (Fig. 1b). Both pH values fluctuated as the following trend: slowly decreased at the first 2 days, probably due to the mineralization of the highly biodegradable OM, leading to the acidification of the compost piles, and NH3 volatilization, then increased sharply until the 6th day, due to the degradation of the biodegradable OM, such as the nitrogen-containing complex, and the enhancement of the ammonification, with a quick decrease after this day until the end of the composting process, due to nitrification, an acidification process (Negi et al. 2020; Zhang et al. 2020).

The OM available in the substrate was used for evaluating the different phases of composting, and the extent of organics removal by microbial degradation was evaluated by OML during aerobic sludge composting (Yaman 2020; Paredes et al. 2001; Santos et al. 201b; Negi et al. 2020). The experimental data of OM degradation in both piles fitted the first-order reaction (Fig. 1c). Though parameter A and k1 only varied slightly between the two piles, the final OMLs of the control and the bio-augmented piles were 64.89% and 68.10%, respectively. This was due to the recalcitrant organic compounds of the compost mixture which hindered the biodegradation process (Santos et al. 2016b). However, bioaugmentation moved the degradation date 1 day ahead (Fig. 1c). Bioaugmentation was a suitable way to improve the humification degree of the composts, shorten the compost time, and accelerate the composting efficiency (Wang and Liang 2021; Costa et al. 2021; Negi et al. 2020). Further study on bioaugmentation with high hydrolyzing activity of poorly degraded material should be noted.

Nitrogen- and sulfur-containing compounds profiles

In this study, the trends of the contents of TN, NH4+, NO3−, and NO2− were similar during the composting process and the difference in the data between the two reactors was great (p< 0.05), especially that of TN and NO3− (Fig. 2a and b). The contents of TN, NO3−, and NH4+ were significantly higher than that of NO2− (p< 0.05). Because of the coupling of assimilatory nitrate and nitrite reduction, the release of nitrite from NO3− reduction was low in the earth (Kuypers et al. 2018).

The contents of TN increased smoothly along the composting process and widened by 28.96% and 39.42% at the end of the process in the control and bio-augmented reactors, respectively. The contributions were mainly from the reduction of total mass caused by OM degradation and the rising of moisture content (Shou et al. 2019; Li et al. 2017; Zhang et al. 2020). TN content in the bio-augmented reactor was 29.84 mg/g DW at the end of maturation phase, about 12.35% higher than that in the control (26.56 mg/g DW) (p< 0.01). That signified the effectiveness of bioaugmentation to conserve nitrogen and mitigate ammonia emission in the compost.

In the control and bio-augmented reactors, the contents of NH4+ increased rapidly during the initial phase, with the maximum of 2.87 and 2.23 mg/g DW on day 6, and then decreased slowly until the end of the maturation process (Fig. 2). During the present process, the evolution of OM and TN decreased the C/N ratio, which was higher in the control than in the bioaugmented pile. A higher C/N ratio may favor ammonification and the dissimilatory nitrate reduction to ammonium (Zhang et al. 2020; Kuypers et al. 2018), leading to more NH4+ and less NO3− accumulations in the control. Low concentration of NH4+ in the bioaugmentation may improve some enzyme activities to a certain degree, such as glutamate synthase, which had a relatively higher affinity for NH4+-N to consume a low concentration of NH4+ as N sources for cell mass synthesis to form organic-N (Du et al. 2019; Shou et al. 2019).
Nitrate contents peaked at 2.40 and 2.84 mg/g DW on day 4, and the mean was 2.01 mg/g DW in the bio-augmented piles, significantly higher than 1.45 mg/g DW in the control ($p < 0.01$) (Fig. 2). Bioaugmentation applied could advance and enhance the nitrification of $\text{NH}_4^+$-N to form $\text{NO}_3^-$.

Nitrification in this study mainly occurred in the mesophilic and the early thermophilic phase, earlier than that reported in the maturation phase (Santos et al. 201b; Shou et al. 2019). Higher nitrate accumulation also could keep pH lower and eliminate ammonia emission (Meng et al. 2016). $\text{NO}_3^-$ coupled with ammonium to enhance the assimilation of nitrogen could prolong N retention and conserve more nitrogen in the pile (Kuypers et al. 2018; Zhang et al. 2020).

The sulfur cycle was closely related to the main odorous substances produced during the composting. In the aerobic condition, many enzymes, such as arylsulfatase (ARS), could...
convert organic sulfur to sulfate. The ARS activity was significantly higher during the maturing phase than other phases (Toledo et al. 2018), which was related to the gradual release of organic sulfur from the compost mixture with the degradation of refractory organic matter (Shou et al. 2019; Santos et al. 201b; Negi et al. 2020). Therefore, the contents of \( \text{SO}_4^{2-} \) were rising gradually and continuously and reached the maxima of 11.67 mg/g DW on day 10 and 12.58 mg/g DW on day 14 in the control and the bio-augmented piles, respectively.

**NH\(_3\) and H\(_2\)S emission during the composting process**

During the thermophilic phase with alkaline pH in both reactors, most ammonium was probably converted to ammonia for the shift of NH\(_4^+\)/NH\(_3\) equilibrium (Chan et al. 2016; Li et al. 2017; Shou et al. 2019). Ammonia emission amount sharply increased to the maxima of 1200 and 1039.8 mg/day on day 4.5 in the control and the bio-augmented piles, respectively (Fig. 3a). Temperature and anaerobic conditions were the main variables to affect H\(_2\)S production and emission, especially in the initial phase of the compost (Zang et al. 2016; He et al. 2018; Toledo et al. 2018). In this study, H\(_2\)S emission occurred on days 0–14, and peaked at 17.52 and 12.84 mg/day in control and experiment piles, respectively (Fig. 3b). After day 14 and day 4, ammonia and H\(_2\)S emissions were under the detection limits, respectively. 3707.52 mg of NH\(_3\) and 37.44 mg of H\(_2\)S were generated in the bio-augmented reactor, reducing 38.00% of 5997.84 mg of NH\(_3\) and 54.32% of 81.96 mg of H\(_2\)S measured in the control, respectively (p < 0.001). The “\( k_2 \)” values of NH\(_3\) and H\(_2\)S obtained were found to be 0.30 day\(^{-1}\) and 0.70 day\(^{-1}\) in the bio-augmented pile, and 0.43 day\(^{-1}\) and 0.71 day\(^{-1}\) in the control, respectively (Fig. 3). Bioaugmentation could greatly reduce the amounts of NH\(_3\)
and H$_2$S emissions and the emission rate of NH$_3$, but affects less on the emission rate of H$_2$S.

Nitrate reduction and sulfate reduction were two important pathways involved in the ammonia and H$_2$S emission over large scales and potentially widespread in the world (Zhang et al. 2020; Toledo et al. 2018; Negi et al. 2020). However, both reductions compete with the electron donor, such as OM, to reduce NO$_3^-$ and SO$_4^{2-}$ (Zhang et al. 2020; Kuypers et al. 2018). With the less content of biodegradable OM in the mature phase, these reductions were lowered. Furthermore, higher aerobic biomass of bioaugmentation inhibited the anaerobic cell activity in the compost, and mitigated the reductions to form NH$_3$ and H$_2$S (He et al. 2018; McGenity et al. 2017). As a result, more NO$_3^-$ and SO$_4^{2-}$ were accumulated in the bioaugmented reactor (Fig. 2a and b) and less NH$_3$ and H$_2$S emission than the control (Fig. 3a and b). Bioaugmentation in the present study could inhibit the denitrification and sulfate reduction pathways to a certain degree (Fig. 4).

**Bacterial community composition and dynamics**

**Diversity, evenness, and similarity of bacterial community**

In this study, the activity and composition of bacterial communities in the 16S rRNA gene annotation results were used to explore the relationship between the truly important functional implementers and functional changes in the compost system (Zhao et al. 2019; Shou et al. 2019; Du et al. 2019).

**Figure 3** Time-course profiles of NH$_3$ (a) and H$_2$S (b) emission

**Figure 4** RDA of the relative abundance of bacterial communities and some environmental factors
The rarefaction curve of the sample was constructed and tended to flatten out at 97% similarity level, and the Shannon-Wiener curve of each sample tended to be flat when the sequencing value was nearly 20000. Samples nearly attained the saturated stage and the sequencing covered more than 99.5% of bacilli. Reads and OTU are listed in Table 2.

Higher biomass for the external addition by bioaugmentation indicated the strong ability of bioaugmentation cultures could survive and function over time in the complex interaction of multiple variables (Table 2). The depression of the biodiversity and the evenness of bacterial community in the thermophilic phase in both piles were a response of the bacterial community to resist the thermophilic condition (Doloman et al. 2020; McGinity et al. 2017; Xin et al. 2017).

Bacterial diversity and abundance directly affect the composting process, and the prevalent physico-chemical conditions also modulate the dynamics of bacteria community succession (Kuyipers et al. 2018; Li et al. 2017; Meng et al. 2016; Du et al. 2019). The result of RDA showed that component 1 (PC1) and component 2 (PC2) explained 88.09% and 8.94% of the data variance, respectively (Fig. 4). There were remarkable differences and dissimilarities of bacterial community among three phases in the same piles. The bacterial community in the thermophilic phase in the bioaugmented pile could influence pH value and the emission of NH₃ and H₂S more significantly than the control.

Bioaugmentation could interfere with the bacterial community succession and augmented the populations’ evenness (E index) and diversity (H index) in the thermophilic phase (Table 2). As a result, the bacterial community in the bioaugmented pile tended to be stable to resist outer fluctuations and achieve the stability of system performance (Shao and Zheng 2014; Xin et al. 2017). Bioaugmentation could be used as a design tool to enhance bacterial diversity and evenness in the compost (Doloman et al. 2020; McGinity et al. 2017).

### Bacterial community shifts in the thermophilic phase

The bacterial community in DSS composting was dominated by the following phyla: Proteobacteria, Bacteroidetes, Actinobacteria, Firmicutes, and Chloroflexi (Shou et al. 2019; Du et al. 2019). The enhancement of populations’ evenness (E index) and diversity (H index) in the thermophilic phase in the bio-augmented pile was mainly from the decrease in the relative abundance (RA) of Proteobacteria and the rising of RA of Bacteroidetes (Fig. 5a).

The RA value of Proteobacteria was absolutely the peak in the whole process, especially in the thermophilic phase with 77.95% and 60.04% of RA in the control and the bioaugmented reactors, respectively. Bioaugmentation greatly depressed 26.69% of OTU number in the thermophilic phase, mainly for the decrease of RA of *Pseudoxanthomonas* from 50.60 to 36.60% (Fig. 5b). *Pseudoxanthomonas* could reduce nitrite but not nitrate with the only production of nitrous oxide (N₂O) (Finkmann et al. 2000; Thierry et al. 2004). This may be one of the reasons to preserve nitrogen as nitrate in the bioaugmented pile.

Bioaugmentation stabilized the RA of Bacteroidetes throughout the composting process (Yaman 2020). Its RA values in the bio-augmented pile were 23.38%, 24.21%, and 28.75% in the initial, thermophilic, and mature phases, and 24.38%, 9.42%, and 27.96% in the control, respectively (Fig. 5b). Bacteria of the Bacteroidetes phylum were considered primary degraders of polysaccharides and were found in many ecosystems (Zhao et al. 2019). Collectively Bacteroidetes had elaborated a few thousand enzyme combinations for glycan breakdown (Lapébie et al. 2019). The fact that some bacteria with a lignocellulose-degrading ability become dominant microorganisms made sense, indicating accelerated composting for enhanced humification as well as compost maturity (Wang and Liang 2021; Shou et al. 2019; Zhao et al. 2019). Bioaugmentation improved the distribution of bacterial community and enhanced the degradation of refractory organic matter.

### Conclusion

Aerobic bioaugmentation could keep pH 6.87± 0.46. Comparing to the control, bioaugmentation produced 9908.60 MJ/day energy, increased 38.75% of NO₃⁻, and mitigated 38.00% and 54.32% of NH₃ and H₂S emissions.

| Coverage | Valid sequence number | OTUᵃ | H   | E   |
|----------|-----------------------|------|-----|-----|
| Control-2 | 0.997423 | 49145 | 1024 | 5.22 | 0.75 |
| Control-6 | 0.996760 | 48593 | 551  | 2.91 | 0.46 |
| Control-20 | 0.996452 | 51046 | 826  | 4.63 | 0.69 |
| Bio-augmented-2 | 0.996941 | 54362 | 1049 | 5.11 | 0.73 |
| Bio-augmented-6 | 0.996441 | 50854 | 576  | 3.48 | 0.55 |
| Bio-augmented-20 | 0.996461 | 50779 | 737  | 4.54 | 0.69 |

ᵃThe similarity level was 0.97
respectively. TN and sulfate contents increased 39.42% and 70.75% at the end, respectively. Bioaugmentation reduced "k" of NH$_3$ from 0.43 to 0.30 day$^{-1}$, but affect less on that of H$_2$S and OM. OM degradation date was moved 1 day ahead. $E$ and $H$ indexes in the thermophilic phase in the bioaugmented pile were enhanced, mainly for the reduction of 22.97% of RA of Proteobacteria and the rising of 157.16% of Bacteroidetes. Bioaugmentation could improve the diversity and the evenness of bacterial community to resist outer fluctuations and achieve the stability of system performance.

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Availability of data and materials All data generated or analyzed in the current study was included in this article.

Author contribution Cheng Qingli, Zhang Longlong, and Wang Dawei contributed to the conception and design of this study. All authors took part in the whole composting process. Parameters were measured by Zhang Longlong, Wang Dawei, and Niu Bochao and analyzed by Cheng Qingli and Zhang Longlong. The first draft of the manuscript was written by Cheng Qingli and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests All authors declare no competing interests.

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