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RESEARCH ARTICLE

Enhanced deodorization and sludge reduction in situ by a humus soil cooperated anaerobic/anoxic/oxic (A2O) wastewater treatment system

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Abstract Simultaneous sludge reduction and malodor abatement in humus soil cooperated an anaerobic/anoxic/oxic (A2O) wastewater treatment were investigated in this study. The HSR-A2O was composed of a humus soil reactor (HSR) and a conventional A2O (designated as C-A2O).The results showed that adding HSR did not deteriorate the chemical oxygen demand (COD) removal, while total phosphorus (TP) removal efficiency in HSR-A2O was improved by 18 % in comparison with that in the C-A2O. Both processes had good performance on total nitrogen (TN) removal, and there was no significant difference between them (76.8 and 77.1 %, respectively). However, NH_4^+–N and NO_3^-–N were reduced to 0.3 and 6.7 mg/L in HSR-A2O compared to 1.5 and 4.5 mg/L. Moreover, adding HSR induced the sludge reduction, and the sludge production rate was lower than that in the C-A2O. The observed sludge yield was estimated to be 0.32 kg MLSS/day in HSR-A2O, which represent a 33.5 % reduction compared to a C-A2O process. Activated sludge underwent humification and produced more humic acid in HSR-A2O, which is beneficial to sludge reduction. Odor abatement was achieved in HSR-A2O, ammonium (NH_3), and sulfuretted hydrogen (H_2S) emission decreased from 1.34 and 1.33 to 0.06 mg/m^3, 0.025 mg/m^3 in anaerobic area, with the corresponding reduction efficiency of 95.5 and 98.1 %. Microbial community analysis revealed that the relevant microorganism enrichment explained the reduction effect of humus soil on NH_3 and H_2S emission. The whole study demonstrated that humus soil enhanced odor abatement and sludge reduction in situ.

Keywords Humus soil · Odor abatement · Sludge reduction · Phosphorus removal

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Introduction

Activated sludge is a widely used treatment process for both domestic and industrial wastewater for decades (Zhang et al. 2015). A2O process is the most commonly used activated sludge approach in waste water treatment plants (WWTPs) for removal of COD, nitrogen, and phosphorus, which is a single activated sludge system incorporating anaerobic, anoxic, and aerobic zones in sequence (Chen et al. 2015). Despite its high efficiency in removing contaminants, it has two major operational problems: (1) it produces large amounts of malodorous gases, which have a negative impact on the workers of sewage treatment plants and local population nearby (Lebrero et al. 2011). (2) In addition, large amounts of excess sludge are generated as another by-product of urban wastewater treatment, making sludge management become another key issue. Malodorous gases, such as H_2S, NH_3, dimethyl sulfide (DMS), and dimethyl disulfide (DMDS), pose acute respiratory toxicity and neurotoxicity (Ho et al. 2008). Since the increasing number of malodorous-related complaints and the recent enforcement of strict environmental regulations, methods of their reduction are of great interest to be investigated (Easter et al. 2008). Sludge treatment systems involve high costs, accounting for up to 60 % of the total operating cost of WWTPs (Tejada et al. 2013). Thus, simultaneous reduce odor emission and sludge production have great significance in developing both environmental friendly and economic wastewater treatment technique.

Many effective techniques have been developed to lower sludge production and malodorous gases emission (Estrada et al. 2011; Ye et al. 2010). Humus soil that contains humic substances posses multiple properties and high structural complexity, which has been a perfect amendment material for microorganism cultivation (Chaturvedi et al. 2006). Recent research has reported that some favorite bacteria could grow in the reactor, such as some functional bacteria in adsorption and degradation of malodorous gases (Chung et al. 2006). Zhu et al. (2011) found that humus soil cooperated sequencing batch reactor (SBR) would enhance phosphorus removal, and the efficiency of soluble orthophosphate (SOP) removal was 97.3 % compared with the removal efficiency of 80 % in the traditional SBR due to the improved dominance of phosphate accumulating organisms (PAOs).

Humus soil cooperated A2O technique offers an attractive treatment option due to the cost-effective and environmental friendly characteristics of the technology (Yin and Zhao 2007). In this process, an HSR is added to a traditional A2O treatment process. Activated sludge cultivated with humus soil in the HSR, and then entered the A2O treatment unit, which significantly influenced the bacterial community. Efficiencies of treatment performance, sludge properties, and sludge productions would change due to the effect of humus soil (Wu et al. 2013; Wu et al. 2009).

To the best of our knowledge, most of the previous research focused on humus soil-enhanced COD, TN, and TP removal efficiencies (Pijuan et al. 2008). However, there is only limited information focusing on the enhanced properties of humus soil on malodor abatement and sludge reduction and the mechanism of the enhancement. Therefore, the objective of this study was to determine the feasibility of adding HSR to A2O for malodorous abatement and sludge reduction. The removal efficiency of HSR-A2O was analyzed compared with traditional A2O, as well as malodorous and sludge production analysis. In this study, bacterial community was also tested in A2O unit in order to reveal the mechanism of malodor abatement and sludge reduction.

Materials and methods

Wastewater, activated sludge, and chemicals

Domestic sewage from Shijing Sewage Treatment Plant of Guangzhou was used as the influent. Average COD, TN, and TP were 276.4, 32.2, and 2.8 mg/L, respectively. All reagents were of analytical grade and purchased from Guangzhou Chemical Reagent Factory, China. Humus soil column was purchased from Kyoritsu Chemical-check Lab. Corp., Japan, and the properties were listed in Table 1. The expansion degree of the humus soil column did not change in either cold water or hot water.

Experimental setup and operational conditions

Two A2O processes (each with a working volume of 2500 L) were studied as the sewage treatment system, with one as the HSR-A2O being cooperated with humus soil and the other one as the C-A2O without humus soil. The A2O reactor was divided into six chambers with anaerobic zones, anoxic zones, and aerobic zones (Fig. 1S). The rate of inflow was set as 300 L/h, and the hydraulic retention time (HRT) of the A2O reactor was 8.5 h with a sludge retention time (SRT) of 10 days. The dissolved oxygen (DO) in the aerobic zone was 1.4–1.8 mg/L. The effective volume of HSR unit was 600 L, and 50 humus soil columns were packed in the HSR. In HSR-A2O, the stored sludge was fed into the HSR, and then 500 L of domestic wastewater mixed with sludge and humus soil. The DO in HSR was 0.3–0.5 mg/L for humification. After 24 h of humification, the sludge was returned back to A2O reactor. The size and the operation condition of the C-A2O were the same as the HSR-A2O. The flow rates of influent and sludge return were controlled by peristaltic pumps (Shenchen Co., Ltd., China). The effluent of the HSR-A2O and C-A2O was monitored every day for COD, TN, NH_4^+–N, NO_3^-–N, TP, and mixed liquor suspended solids (MLSS). All tests were conducted at ambient temperature of 25 ± 2 °C.

Analytical methods

The mixed liquors were immediately filtered through millipore filter units (0.45 lm pore size) for analysis of the COD, TN, NH_4^+–N, NO_3^-–N, and TP. COD was measure with a quick analysis apparatus (Lian-hua Tech. Co., Ltd, 5B-1, China).NH_4^+–N, NO_3^-–N were analyzed using a flow injection

Table 1 Properties of humus soil column

Compression strength	Water content (%)	pH	Organic matter (%)	Inorganic matter (%)				
				SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
0.667	10	2.3	<30	≥50	<3	≤4	≤0.3	≤0.3

apparatus (Quick Chem8500, Lachat instrument, USA). TN was measured using a Vario TOC cube (Elementar, Germany). TP was measured according to the Standard Methods for the Examination of Water and Wastewater (State Environmental Protection Administration of China 2002). Mixed liquor suspended solids (MLSS) was analyzed using the standard methods (APHA 1998). Odor was collected inside the anaerobic, anoxic, and aerobic tank, and the concentrations reported are measured maximum. H_2S, NH_3, DMS, and DMDS were tested as the typical malodorous gases in this study. NH_3 was measured using according to the Standard Methods for the Examination of Water and Wastewater (State Environmental Protection Administration of China 2002).The concentration of H_2S, DMS, and DMDS was determined by a headspace-GC method using a gas tight syringe. The GC (CP-3800, Varian) was equipped with a PFP detector and a GC-GasPro column (J W Scientific).

Calculation of observed sludge yield

The observed sludge yield, defined as the ration of produced sludge (ΔMLSS) to the time, was used to evaluate the sludge reduction capacity of HSR-A2O. The ΔMLSS consisted of the increase biomass quantity in the A2O process and the cumulative sludge from excess sludge discharge and effluent.

Activated sludge characteristics

Sludge organic component analysis was obtained using leaching process. After leaching for 12 h, organic content was measured by potassium dichromate method. Fulvic acid and humin should be separated using H_2SO_4 and NaOH before test by potassium dichromate method.

Analysis of microbial community

The microbial community of sludge in anaerobic, anoxic, and aerobic tank of the HSR-A2O and C-A2O were analyzed by Guangdong Institute of Microbiology using multiple tube fermentation technique.

Quality assurance and quality control

All of the analytical experiments were performed in triplicate, and the results presented were average values of the three replicates. The standard deviations for all measurements ranged from 1.0 to 8.0 %.

Results and discussion

Contaminants removal performance of the C-A2O and HSR-A2O processes

In order to evaluate the effect of humus soil on the contaminants removal, the COD, TN, TP removal efficiency of the C-A2O and HSR-A2O was compared. As seen from Fig. 1a, b, the COD and TN removal efficiency in HSR-A2O had no significant differences from that in C-A2O. However, HSR-A2O was able to improve phosphorus efficiency by 18 %

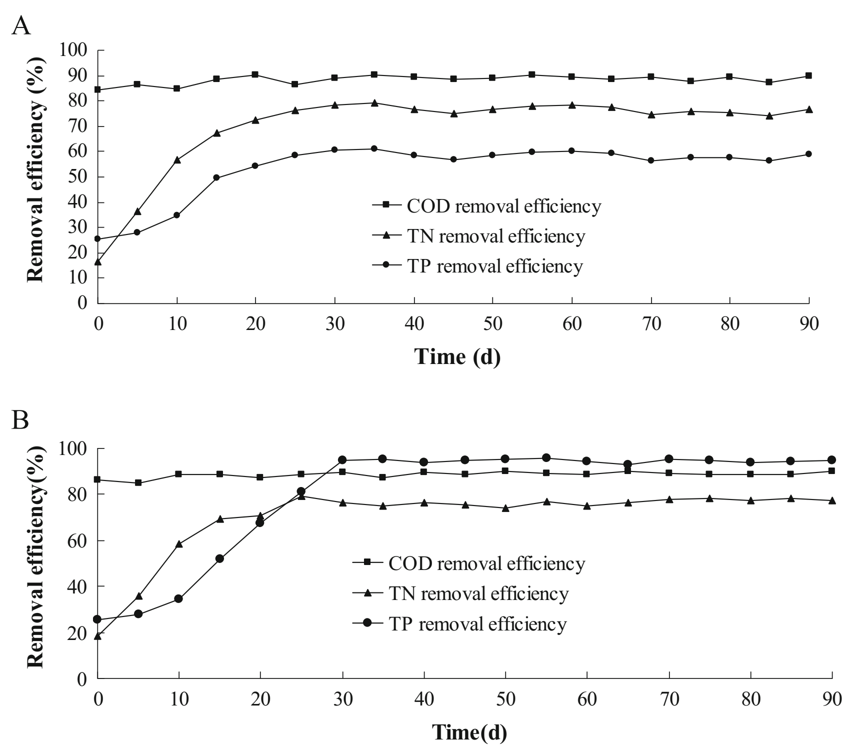

Fig. 1 Variations of contaminants removal performance of the two A2O process. **a** conventional A2O; **b** HSR-A2O

Table 2 Characteristics of the influent and effluent in the C-A2O and HSR-A2O

Phase	Process	COD(mg/L)	NH_4^+–N(mg/L)	NO_3^-–N(mg/L)	TN(mg/L)	TP(mg/L)
Influent	C- A2O HSR- A2O	276.4 ± 35.8	28.2 ± 3.2	nd	32.2 ± 3.2	2.8 ± 0.1
Anaerobic	C- A2O	54.3 ± 11.1	14.7 ± 0.9	nd	16.9 ± 0.8	8.4 ± 0.4
	HSR- A2O	56.4 ± 9.5	14.2 ± 0.7	nd	16.7 ± 1.2	9.6 ± 0.5
Anoxic	C- A2O	42.5 ± 8.5	3.5 ± 0.2	2.4 ± 0.1	8.7 ± 0.4	3.7 ± 0.1
	HSR- A2O	43.6 ± 9.8	3.5 ± 0.1	2.4 ± 0.1	8.9 ± 0.6	2.6 ± 0.13
Effluent	C- A2O	34.5 ± 6.1	1.5 ± 0.08	4.5 ± 0.2	7.5 ± 0.28	0.64 ± 0.03
	HSR- A2O	34.8 ± 6.8	0.3 ± 0.01	6.7 ± 0.2	7.8 ± 0.42	0.28 ± 0.01

The date reported are the averages and standard deviations after the system being stable(after te 30th day)

compared with that of C-A2O. The average of COD, NH_4^+–N, NO_3^-–N, TN, and TP in the C-A2O and HSR-A2O during the entire experiment is shown in Table 2.

COD removal efficiency in both C-A2O and HSR-A2O maintained 82 to 91 % from the beginning of sewage treatment process. At the end of anaerobic phase, the COD in C-A2O and HSR-A2O reduced to an average of 54.3 and 56.4 mg/L in these two processes, respectively. These observations indicated that most COD in the influent were consumed during the anaerobic phase. This could be attributed to that activated sludge adsorbed contaminants and microorganisms utilized organic pollutants as extracellular carbon to store inside cells. Both processes had good performance on TN removal, and there was no significant difference between them (76.8 and 77.1 %, respectively). However, NH_4^+–N and NO_3^-–N was reduced to 0.3 and 6.7 mg/L in HSR-A2O compared to 1.5 and 4.5 mg/L. The average effluent phosphorus and corresponding removal efficiencies were 0.28 mg/L and 90 % in HSR-A2O and 0.64 mg/L and 72 % in C-A2O. The NO_3^-–N and phosphorus were revealed to be simultaneously utilized in denitrifying dephosphatation (Liu et al. 2007).This would partially explain why the TP removal in HSR-A2O was higher than that in C-A2O. Previous research found that higher concentration of NO_3^-–N in oxic pool will be conductive to phosphorus removal (Panswad et al. 2003). The group of polyphosphate accumulating organisms (PAOs) is responsible for phosphorus removal. Another study explored that the reduction role of glycogen-accumulating organisms (GAOs) played by humus soil reactor would lead to more available carbon source for PAOs (Broughton et al. 2008). Therefore, adding the humus soil improved the relative dominance of the PAOs in HSR-A2O, which would significantly improve the phosphorus removal.

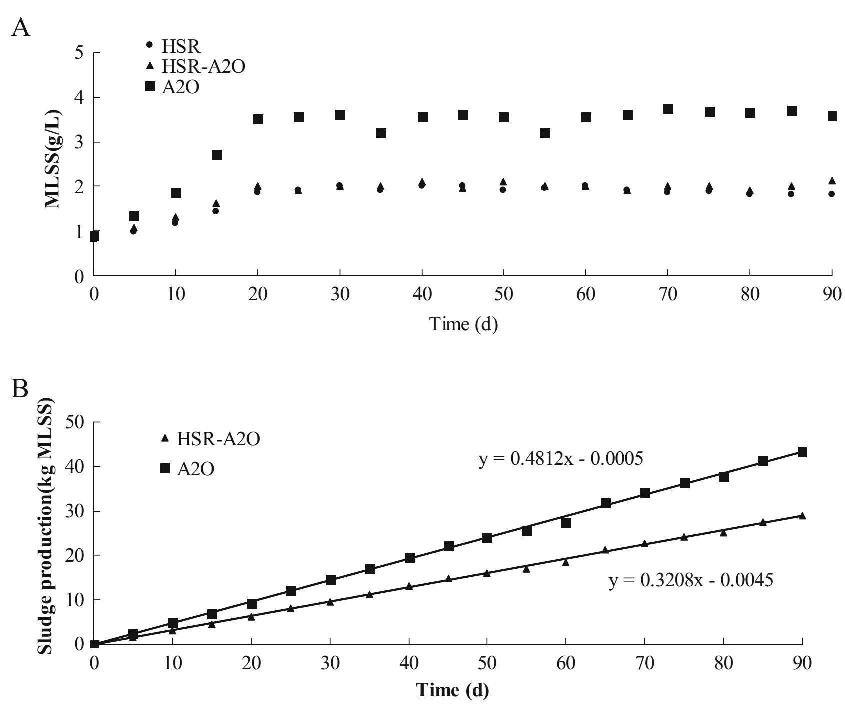

Fig. 2 Differences of sludge yields in the C-A2O and HSR-A2O. **a** sludge concentration; **b** cumulative sludge production

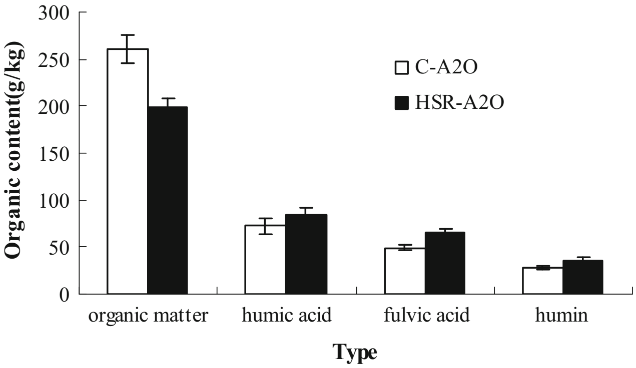

Fig. 3 Organic component in activated sludge

Sludge yields of the C-A2O and HSR-A2O process

The feasibility of adding humus soil to A2O process to achieve sludge reduction was studied by comparing the MLSS in the C-A2O and HSR-A2O, as well as the cumulative sludge production of C-A2O and HSR-A2O, and the experimental results are present in Fig. 2. MLSS in the C-A2O increased from 0.9 to 3.6 g/L and maintained at about 3.6 g/L. MLSS in the HSR and HSR-A2O increased from 0.8 to 2.0 g/L and maintained around 2.0 g/L. As seen from Fig. 2b, the sludge production rate in HSR-A2O and C-A2O was 0.32 and 0.48 kg MLSS/day. During the entire experiment, the total sludge production was 28.9 kg, 33.5 % lower than that of the C- A2O. Based on the comparison of sludge production in the C-A2O and HSR-A2O, it was obvious that sludge reduction was achieved in the HSR-A2O. This was mainly due to the following reasons: (1) humified activated sludge improved the property of sludge dewatering, thus resulting in sludge reduction. (2) The sludge retention time was 24 h higher in HSR-A2O, and more microorganisms entered a state of endogenous respiration, resulted in sludge reduction. (3) Microbial community changed that the amount of glycogen-accumulating organisms was decreased.

Activated sludge characteristics

Organic component analysis of activated sludge in C-A2O and HSR-A2O was obtained, and the results are displayed in Fig. 3. Organic matter content of the activated sludge in HSR-A2O was 198.4 g/kg, which is significant lower compared to 260.4 g/kg in C-A2O. However, humic acid content in HSR-A2O (84.5 g/kg) was higher than that in C-A2O (72.5 g/kg), indicating that activated sludge underwent humification and produced humic acid in humus soil reactor. After 24 h of incubation, the activated sludge characteristics changed, and the results were displayed in Table 3. SVI ranges 70 to 100 for activated sludge with good settleability in domestic wastewater treatment (Zhang et al. 2000). During the 90 days stable operation, the SVI of HSR-A2O remained at 75–87, which was much lower than that in C-A2O (127–145). A survey of 100 nutrient removal processes showed that the best sludge settling characteristics were found with biological phosphorus removal, which could partially explain why phosphorus removal was improved in HSR-A2O (Andreasen and Sigvardsen 1996). By analyzing the sludge morphology of this system, the particle size of activated sludge in the HSR-A2O (d_{50}:136–148) was much higher than that in the C-A2O (d_{50}:84-96). Granular activated sludge started to form, with the bigger particle size being dominant in HSR- A2O process. Sludge settleability of activated sludge is greatly related to the EPS properties (Dierdonck et al. 2013). Although EPS is essential to sludge floc formation, excessive EPS will weaken cell attachment and deteriorate floc structure, resulting in poor solid-liquid separation (Yang and Li 2009). The total EPS contents were 57.07–87.85 mg/g VSS, which were much lower than C-A2O process (108.45–132.28 mg/g VSS). It had been reported the EPS content extracted from granular sludge was lower than that from flocculent sludge because granular sludge was densely packed while flocculent sludge was loosely aggregated (Liu and Fang 2002). In this study, the lower EPS played an important role in changing sludge microstructure and improved the sludge settling ability.

System performance in terms of H_2S, NH_3, DMS, and DMDS removals

Influence of the HSR on the odor emission was investigated, and the odors detected in this study were H_2S, NH_3, DMS, and DMDS. The odor emissions at different sampling sites during the treatment process are present in Table 4, and the data reported are measured maximum of the concentration. It is observed that humus soil significantly decreases the NH_3 and H_2S emission. DMS and DMDS emission of anaerobic tank in HSR-A2O decreased from 0.057 and 0.045 mg/m^3 to 0.025 and 0.025 mg/m^3, respectively. More than 95 %

Table 3 The comparison of activated sludge properties

Item	Anaerobic site		Anoxic site		Aerobic site	
	HSR-A2O	C-A2O	HSR-A2O	C-A2O	HSR-A2O	C-A2O
SVI(mL/MLSS)	75	127	87	145	79	132
d_{50}	142	96	136	84	148	90
EPS content(mg/g VSS)	0.025	0.0570	0.025	0.0275	0.025	0.025

Table 4 The emission concentrations of different odors

Odor	Anaerobic site		Anoxic site		Aerobic site	
	HSR-A2O (mg/m^3)	C-A2O (mg/m^3)	HSR-A2O (mg/m^3)	C-A2O (mg/m^3)	HSR-A2O (mg/m^3)	C-A2O (mg/m^3)
NH_3	0.06	1.33	0.05	1.02	0.03	0.273
H_2S	0.025	1.34	0.025	0.36	0.025	0.03
DMS	0.025	0.057	0.025	0.0275	0.025	0.025
DMDS	0.025	0.045	0.025	0.0265	0.025	0.025

The odor gases were collected inside the tank, and the concentrations reported are measured maximum

reduction efficiency of NH_3 and H_2S emission in HSR-A2O was achieved, and most of the gas was eliminated at anaerobic tank. The release of NH_3, H_2S, DMS, and DMDS was attributed to the protein degradation by means of microbial transformation in anaerobic conditions (Adams et al. 2008; Higgins et al. 2008). In HSR, specific microorganisms in humus soil incubated and enriched, which was able to utilize the odor for cell protein synthesis. Thus, the nitrogen and sulfur converted into acetic acid and amino acids polymeric compounds. Previous study identified various forms of nitrate-reducing and sulfide-oxidizing in humus soil, which can inhibit the production of H_2S and NH_3 (Talaiekhozani et al. 2016). Therefore, the high odor abatement performance was probably due to the efficient microbial pollutant uptake in the mixed liquor. All the odor emissions in HSR-A2O meet the ambient air standards.

Microbial community analysis

The effect of humus soil reactor on microbial community was studied, and the results are displayed in Table 5. It can be observed from Table 5 that microorganisms with the ability of H_2S, NH_3, DMS, and DMDS adsorption and degradation obtained concentration, activation, and proliferation in anaerobic tank, such as *Bacillus*, *Pseudomonas*, and *Photosynthetic bacteria* (PSB). Thus, the odor removal efficiency in HSR-A2O significantly improved. Nitrifying bacteria in the activated sludge also got multiplication, resulted in NH_4^+–N, NO_2^-–N consumption, and formation of NO_3^-–N. This could be the probably reason that NO_3^-–N concentration in aerobic tank improved in HSR-A2O system. In addition, due to the interaction between humus soil and activated sludge, the sludge structure changed.

Conclusion

The HSR-A2O could be an efficient technology for simultaneous contaminants removal, sludge reduction, and malodorous abatement. In HSR-A2O, adding humus soil did not deteriorate the COD removal and TN removal, while TP removal efficiency in HSR-A2O was improved by 18 % in comparison with that in C-A2O. Moreover, adding HSR induced the sludge reduction, and the sludge production rate was 33.5 % lower than that in the C-A2O. Odor emission reduction was achieved in HSR-A2O, with the corresponding NH_3 and H_2S emission reduction efficiency of 95.5 and 98.1 %. Sludge organic component and properties changes were observed, which is beneficial to sludge reduction, and odor abatement. Microbial community analysis revealed that the relevant microorganism enrichment explained the reduction effect of humus soil on NH_3 and H_2S emission.

Table 5 Different microbes in the sludge samples

Bacteria(CFU/mL)	Anaerobic site		Anoxic site		Aerobic site	
	HSR-A2O	C-A2O	HSR-A2O	C-A2O	HSR-A2O	C-A2O
Photosynthetic bacteria	4.2×10^4	6	2.2×10^3	8	94	7
Thiobacillus	1.1×10^3	4.4×10^4	168	1.8×10^4	98	1.4×10^4
Actinomycetes	785	1	845	45	435	76
Bacillus	5.0×10^3	8.4×10^5	8.2×10^3	1.2×10^6	2.5×10^4	1.4×10^6
Aspergillums	0.3×10^9	2.0×10^3	1.5×10^7	2.5×10^3	2×10^7	1.3×10^3
Nitrifying bacteria	–	8	4	65	8	51
Pseudomonas	–	3.1×10^3	11	2.4×10^3	28	4.3×10^3
Saccharomyces	–	4.5×10^3	16	2.8×10^3	7	1.7×10^3

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