


 Cite this: *RSC Adv.*, 2021, **11**, 15977

Reducing odor emissions from feces aerobic composting: additives

 Ping Zhu,^a Yilin Shen,^a Xusheng Pan,^a Bin Dong,^{*b} John Zhou,^c Weidong Zhang^d and Xiaowei Li^{id *a}

Aerobic composting is a reliable technology for treating human and animal feces, and converting them into resources. Odor emissions in compost (mainly NH₃ and VSCs) not only cause serious environmental problems, but also cause element loss and reduce compost quality. This review introduces recent progresses on odor mitigation in feces composting. The mechanism of odor generation, and the path of element transfer and transformation are clarified. Several strategies, mainly additives for reducing odors proven effective in the literature are proposed. The characteristics of these methods are compared, and their respective limitations are analyzed. The mechanism and characteristics of different additives are different, and the composting plant needs to be chosen according to the actual situation. The application of adsorbent and biological additives has a broad prospect in feces composting, but the existing research is not enough. In the end, some future research topics are highlighted, and further research is needed to improve odor mitigation and element retention in feces compost.

Received 15th January 2021

Accepted 5th March 2021

DOI: 10.1039/d1ra00355k

rsc.li/rsc-advances

1. Introduction

With the upgrading and expansion of the livestock and poultry industry, the production of livestock and poultry manure has increased dramatically. According to the statistical yearbook of China, the annual production of livestock manure in China is about 3.8×10^9 ton.¹ Unfortunately, the drastic world population increase (exceeded 7.6 billion people in 2018) has led to serious environmental problems for human waste management to become more severe.² Based on a wet weight of 350 g–400 g per person per day, it is estimated that over one billion wet tons of human feces are produced every year worldwide, and these production levels continue to increase.³ In terms of the composition, animal and human feces contain considerable nutrients, heavy metals and pathogens.⁴ If feces are discharged into the water without treatment, it will pollute water sources. Nutrients will cause water eutrophication, and the organic matter in feces will rot. This results in the breeding of mosquitoes and flies, and the production of odor, bringing

troubles to surrounding residents' daily life.⁵ If heavy metals in water enter the human body through the food chain, they will accumulate in the human body and cause various diseases, such as kidney damage and bone pain. In 1956, the Japan Minamata disease events, which shocked the world, were caused by mercury pollution, resulting in thousands of Japanese citizens suffering horrific neurological injury.⁶ Moreover, pathogens, viruses and the eggs of parasites contained in feces may cause the spread of various diseases, such as typhoid fever (including *Salmonella* infection), dysentery (including *Shigella* infection), polio and hepatitis A.⁷ These pathogens are mainly spread through contaminated food and water. If they contaminate drinking water, it will cause more serious and widespread disease problems. In 2015, a fishing village polluted the water source with feces, resulting in an outbreak of cholera. The outbreak caused illness and death of villagers, involving 65 cases and two deaths.⁸ As an ignored pollutant resource, antibiotic resistance genes in feces are also very harmful.⁹ They could be absorbed by crops and enter the human body through the food chain, causing damage to the liver and kidney function, the destruction of normal human flora, and harming public health.^{10,11}

The disposal of feces is a worldwide hygiene and health problem. Especially in developing countries, approximately 31% of people resort to inadequate feces disposals.¹² In general, most feces will be eliminated as waste, not as precious resources.¹³ Feces contain not only a large amount of organic matter, but also nitrogen, phosphorus, potassium and other crop nutrients, so they are good raw materials for composting.¹⁴ Composting can reduce the volume of feces, and stabilize and

^aSchool of Environmental and Chemical Engineering, Shanghai University, 99 Shangda Road, Shanghai 200444, People's Republic of China. E-mail: lixiaowei419@shu.edu.cn

^bState Key Laboratory of Pollution Control and Resources Reuse, National Engineering Research Center for Urban Pollution Control, College of Environmental Science and Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, PR China. E-mail: dongbin@tongji.edu.cn; Tel: +86-021-66137747

^cSchool of Civil and Environmental Engineering, University of Technology Sydney, 15 Broadway, Sydney, NSW 2007, Australia

^dSchool of Petroleum and Chemical Engineering, Shenyang University of Technology, 30 Guanghua Street, Hongwei District, Liaoyang City, Liaoning Province 111003, People's Republic of China



humify feces under aerobic conditions.^{15,16} It can also safely and effectively treat feces to avoid the spread of pathogenic bacteria and microorganisms.¹⁷ The application of mature compost into soil can improve soil fertility, provide nutrients for crops, and minimize the risk of weeds and land degradation.^{18,19} In general, mature manure compost is a good fertilizer.^{20,21}

However, one of the most important problems of feces composting is the emission of various gases and the accompanying odors. The main odorous gases produced during the feces composting process include nitrogen-containing gases and volatile sulfur compounds (VSCs). The nitrogen-containing gases mainly include ammonia (NH_3) and nitrous oxide (N_2O). 16%–74% of the initial total nitrogen (TN) is lost *via* such emissions during composting, which accounts for up to 94% of the TN loss, and the remaining TN loss is mainly in the form of leachate.^{22,23} NH_3 -N release accounts for approximately 80% of the TN loss, which is the main odorous nitrogen-containing gases.^{24,25} About 0.1%–9.9% of the initial TN is lost as N_2O . N_2O is not as smelly and toxic as NH_3 , but it is a greenhouse gas that is harmful to the environment.²⁶ Meanwhile, about 50% of the total sulfur is lost in the form of VSCs. Common VSCs mainly include hydrogen sulfide (H_2S), methyl mercaptan (MeSH), dimethyl sulfide (Me_2S), dimethyl disulfide (Me_2SS), carbonyl sulfide (COS) and others. The first three VSCs are the main odorous sulfur-containing gases.²⁷ Among them, H_2S is the most released VSCs, accounting for about 39%–43%.²⁸ In general, NH_3 and VSCs are dominant odors during aerobic composting, and they are corrosive and toxic.²⁹ Even if their concentration is very low in the air, they bring bad odor, pollute the environment, and adversely affect human health. Moreover, the overflow of gas causes element and nutrient loss, and reduces the value of the fertilizer. The objectives of this review are to introduce the available strategies for reducing odor emissions during feces aerobic composting, mainly from the perspective of additive use, which not only relieve odor issues, but also maintain nutrients in mature compost materials, improving their value as a synthetic fertilizer substitute.^{30,31}

2. Odor generation during composting

In order to effectively control the odors, it is necessary to understand its generation and emission principles, and the path of element transfer and transformation. In this way, corresponding measures can be taken from the source, process or end to reduce emissions.

2.1 Transfer and transformation of N in composting

During the composting process, the initial form of nitrogen is mainly organic nitrogen in the fresh feces. N can be found mainly in proteins, nucleic acids, amino acids and other organic substances in molecular form.³² Ammonification occurs in the first stage of the composting process. Proteinaceous materials are broken down by various microorganisms, including bacteria and fungi, and organic nitrogen is mineralized to ammonia ($\text{NH}_3(\text{l})$) in the liquid phase, which combines

one proton (H^+) to form NH_4^+ . The $\text{NH}_4^+/\text{NH}_3$ transformation is bilateral.³³ The peak value of the ammonification usually coincides with the maximum biodegradation time.^{34,35} If the density of the ammoniating agent in the composting raw materials is high, such as fresh hen feces, then the ammonification process will proceed quickly. During the composting process, under high temperature (65–70 °C) and slightly alkaline pH conditions (8.4–9.0), the NH_3 -N form is easily volatilized in the gaseous state and lost.³⁶ The formation of N_2O is related to NO_3^- . In addition to the original NO_3^- , $\text{NH}_4^+/\text{NH}_3$ may be absorbed by microorganisms into organic nitrogen, or it may be converted to nitrate (NO_3^-) by nitrification under the action of ammonia-oxidizing bacteria or archaea (AOB or AOA) and nitrite-oxidizing bacteria (NOB).³⁷ Even in aerobic composting, local anaerobic zones are inevitable. There will be problems, such as excessive oxygen consumption rate, insufficient oxygen supply, uneven substrates, and local agglomeration. In the anaerobic zone, NO_3^- -N will be converted to N_2 under the action of denitrifying bacteria (DNB).³⁸ In the process of denitrification to N_2 , N_2O is the intermediate product.

The transfer and transformation process is shown in Fig. 1. During feces composting, nitrogen-related conversion reactions may occur simultaneously, including ammonification, NH_3 assimilation, nitrification, and denitrification.³⁹ The TN loss mainly occurs in the thermophilic stage, which is estimated to account for 40–70% of the initial N content.⁴⁰

2.2 Transfer and transformation of S in composting

Similar to nitrogen, sulfur mainly exists in the organic form at the initial stage of composting. Organic sulfides in raw materials mainly include sulfur-containing proteins, sulfur amino acids, thiamine acid, sulfonate, and others.⁴¹ As the compost process progresses, these organic sulfides are mineralized under the action of enzymes, typically like arylsulfatase.⁴² Generally, in aerobic composting, the final product of the organic sulfide mineralization should be sulfate (SO_4^{2-}).⁴³ However, in the actual aerobic composting process, local anaerobic zones exist. The local anaerobic zone is very suitable

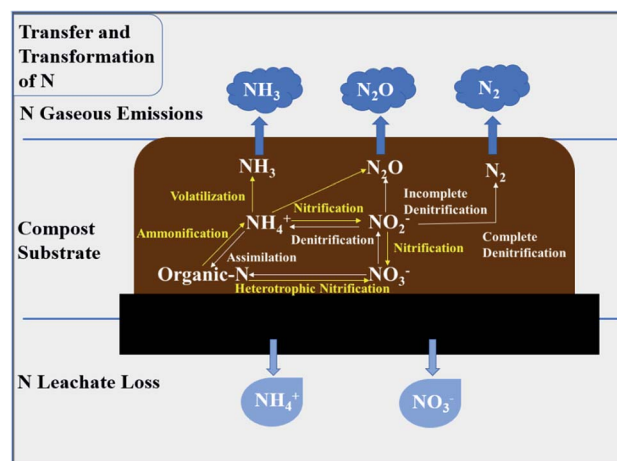


Fig. 1 Transfer and transformation of N in composting.



for the propagation of anaerobic bacteria. Sulfate-reducing bacteria (SRB) are anaerobic, and organic matter will be degraded to generate H_2S under its action.^{44,45} Additionally, SRB can use sulphate as the terminal electron acceptor (thiosulfate and sulfite will also be used), reducing them into H_2S .^{41,46} H_2S is mainly produced when the oxidative redox potential (ORP) in compost is low. Hypoxia causes low ORP, which is also the main reason for the generation of H_2S .⁴⁷ During the formation of H_2S , other reduced sulfur compounds (RSC) will also be produced, such as MeSH , Me_2S , Me_2SS , and others. The transfer and transformation process are shown in Fig. 2. The former is due to the degradation of methionine and methylation of H_2S ; the latter two are the products of methylation and oxidation of MeSH .⁴⁸ These VSCs are the main source of odors during composting, and the most important bacteria in the production of these VSCs are SRB.^{27,46} In general, poor O_2 transfer caused by insufficient aeration is always considered as the main reason for odorous gas production during composting.⁴⁹ The pile temperature can also play an important role in the volatilization of odors, depending on their vapor pressure.⁵⁰ All VSCs are mainly released during the early stage of composting and reach the peak at the highest composting temperature, which is usually also the peak of microbial activity.⁵¹

3. Odor control during composting

The transfer and transformation process of N mentioned above reveals the mechanism of inhibiting the release of NH_3 : (1) reducing organic nitrogen mineralization, which may affect the mineralization and maturation of compost. (2) Increasing the NH_4^+ to NH_3 ratio (decreasing the pH); the range for this manipulation is however narrow. (3) Promoting NH_4^+ / NH_3 assimilation (promoting related microorganisms). (4) Promoting NH_3 oxidation (promoting related microorganisms and oxygen supply).³³

Similarly, the mechanism of sulfide production suggests that VSCs emissions can be reduced by increasing the ORP.⁵² A common method for increasing the ORP is to add

thermodynamically favorable electron acceptor compounds. Many oxidants can achieve corresponding effects.^{53,54} In addition, inhibiting the growth of SRB and raising the pH can reduce the formation of sulfides.⁴⁴

3.1 Adjustment of the composting conditions

Changes in the composting conditions have a certain impact on odor production and emissions. Successful composting must satisfy various conditions. Basic factors, such as O_2 , pH, and temperature, should be in the appropriate range. If composting can ensure that these conditions are within a reasonable range, appropriate adjustments to reduce odor emissions are the most convenient and feasible control measures. Temperature is one of the most important factors in the composting process. High temperature will promote the diffusion of odors, and it also means that the activity of microorganisms is active and will generate more odors. However, if the odor emission is suppressed by reducing the temperature, it will lead to a decrease in the compost quality and maturity. In other words, there is no range for temperature adjustment, so no discussion is made.

3.1.1 Oxygen (O_2). According to the formation mechanism of NH_3 and VSCs mentioned above, the O_2 content should have a great influence on the generation of odors during composting.⁵⁰ From the perspective of NH_3 , the increase in the oxygen content should promote NH_3 oxidation, thereby reducing the release of NH_3 . The emission of VSCs is mainly due to the insufficient oxygen supply, and the O_2 feedback control could reduce the VSCs production.⁵⁵

The O_2 concentration in the compost pile is controlled by aeration. Shortening the aeration interval or aerating continuously to maintain a high O_2 concentration in the pile is an effective strategy for restraining the VSCs production, but the effect on NH_3 is not ideal.⁴⁴ In actual operation, due to the blow-off effect caused by aeration, it may cause an increase in the gas emissions from compost.^{18,62} Some studies have confirmed this view that an increased aeration rate is responsible for an increase in the NH_3 emission.^{56,57} In other words, increasing the aeration will increase the NH_3 emissions. A moderate increase in aeration will reduce the emission of VSCs, but an excessive increase will also increase its emission. Moreover, increasing the aeration will accelerate the temperature loss of the substrates, which may lead to compost failure. In general, it is a bit difficult to reduce the generation of odors by aeration.

3.1.2 pH. The pH changes as the compost progresses. In the initial stage of composting, the release of organic acids leads to a decrease in pH. After that, the organic acid is further decomposed, and various sulfur-containing compounds are decomposed to produce a certain amount of S^{2-} , which is released after being combined with H^+ , thereby reducing the H^+ content in the reactor and increasing the reactor pH. The NH_3 released by mineralization also increases the pH. However, the subsequent nitrification reaction will release H^+ , which may cause the pH to fall again.^{58,59}

The pH value affects the NH_4^+ to NH_3 ratio. Liang *et al.* simulated the NH_3 volatilization mechanism under composting conditions, confirming that a large amount of ammonia

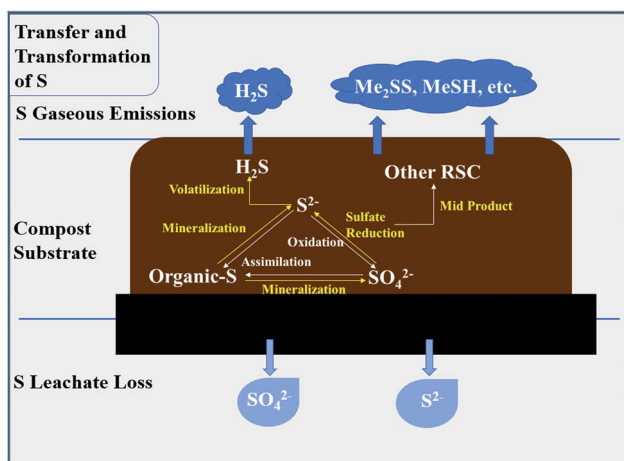


Fig. 2 Transfer and transformation of S in composting.



volatilization occurs at a high pH.⁶⁰ Contrary to NH₃, H₂S is an acidic gas; thus, the alkaline initial pH is the main factor for the reduction of H₂S emissions. An alkaline environment can keep H₂S mostly in the ionic forms, and can also absorb the generated H₂S.⁶¹ Lowering the pH of the compost will reduce NH₃ production, but will increase the VSCs emissions.^{62,63} Gu *et al.* also obtained similar results. After reducing the pH of compost, the cumulative NH₃ emissions and TN losses reduce by 47.80% and 44.23%, but the emissions of VSCs and TS losses increase.¹⁰⁸ In a word, reducing the odors by adjusting the pH is not feasible.

3.2 Composting additives

As mentioned above, the adjustment of the composting conditions can only reduce one of the odorous gases, but promotes the other odors. Moreover, in order to obtain mature compost products, the requirements for basic conditions are already complicated. In other words, even if these conditions are adjusted, the operable range is very narrow. Once the composting environment does not meet the growth conditions required by composting microorganisms, it can easily lead to composting failure.

Composting additives are a good choice for regulation. They generally do not have much impact on the environmental conditions of composting. They can reduce odors by providing porosity, adsorbing gas, and others. Commonly used additives in composting treatment include composting bulking agent, chemical agents, adsorbent, microbial agent, mature compost, and others.

3.2.1 Composting bulking agent. Composting bulking agent is a common additive in composting. In the actual operation of feces composting, especially human feces, feces are often mixed with urine, which results in high water content. Moreover, there are few organics in human feces that can be used by composting microorganisms. In order to adjust the water content of the substrate and provide organic matter, the feces and bulking agent are often mixed in a certain proportion. Common bulking agent mainly include agricultural by-products, such as cornstalks, rice husk, and mushroom bran, which can not only adjust composting conditions, but also recycle waste.

Cornstalks have been used as a composting bulking agent in many studies.⁶⁴ Zhang *et al.* added cornstalks to the compost, and the TN loss of the compost dropped from 45.8 to 24.9%.⁶⁵ In the study by Li *et al.*, the addition of cornstalks reduced the total NH₃ emissions by 30.5%.⁷⁴ Cornstalks can absorb a considerable amount of NH₄⁺/NH₃, avoid the formation of leachate and reduce the nitrogen loss from the leachate.^{66,67} However, many studies have shown that the inhibition effect of cornstalks on NH₃ is not obvious, at only about 6% of the inhibition effect.^{68,69} This is because the addition of cornstalks increases the pH value and the aeration of the substrate, which accelerates the decomposition and conversion of organic matter, so its effect on reducing the NH₃ emissions is not so obvious.⁷⁰

Compared with NH₃, cornstalks can significantly reduce the VSCs emissions. Zhang *et al.* added cornstalks to the compost, and the volatilization of VSCs was reduced by nearly 70%.⁶⁵

Yuan J. *et al.* and Elwell D. L. *et al.* also got similar data.^{68,71} Due to the presence of urine, the water content of feces is generally relatively high. The moisture content of feces will cause anaerobic decomposition conditions (by limiting free air space), which causes odors.⁷² Cornstalks have a low density and low moisture content. Mixing cornstalks with feces can improve the sizes and numbers of inter-particle voids, providing air space in the composting materials and regulating the water content of materials.⁷³

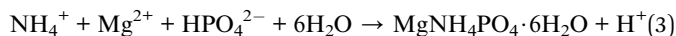
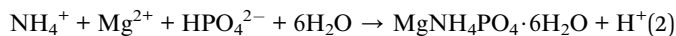
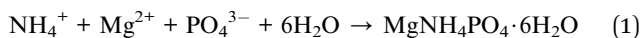
In addition to cornstalks, much bulking agent can also inhibit NH₃ and VSCs. Li *et al.* pointed out that due to the lower pH of the mushroom substrate, its inhibition of NH₃ is higher than that of straw cornstalks (50% vs. 30%), but its adsorption effect on VSCs is not as good as straw (72% vs. 80%). The sawdust is light and the particle size is very small, showing a powder state, which can be wrapped tightly on the surface of the material-like flour. This good adsorption and contact effect can effectively adsorb odors.⁷⁴ In general, the co-composting of bulking agent and feces is a viable option.

3.2.2 Chemical agents. Adding chemical agents to the compost matrix, odors can be removed by chemical reactions. Ferric chloride (FeCl₃) has been widely used to remove NH₃ from wastewater.^{75,76} Iron salt has also been used as a pretreatment to control VSCs in anaerobic digestion.^{77,78} Although there are not many applications of iron salts in composting, some studies have proved that using FeCl₃ to remove odors in composting is feasible. Yuan *et al.* added FeCl₃ to the compost to reduce NH₃ emissions by 38% compared to the control group.⁶⁸ The reduction of NH₃ emissions can be attributed to FeCl₃ being an effective flocculant, and causing coagulation to occur. H₂S emissions have been reduced by 33% compared to the control group. Iron salts can react with dissolved sulfide through numbers of different pathways to form elemental sulfur and sulfates, and decreasing the dissolved sulfide concentration can decrease the potential for H₂S to be generated.^{77,79} In anaerobic treatment, the Fenton method has been shown to improve the biodegradability of waste water.^{80,81} In some areas, people dump food waste into toilets and discharge them together with feces. The oil and grease in food waste will inhibit the microorganisms in the composting process. The Fenton method is beneficial to both the subsequent biological treatment of odors and the quality of compost products.

Struvite (NH₄MgPO₄·6H₂O) crystallization has been considered as an effective process for nitrogen conservation during composting. When magnesium and phosphorus salts are mixed with composting materials, NH₄⁺-N can be conserved in the form of struvite, a slow-release fertilizer.^{82,83} Ren *et al.* reported that the addition of magnesium hydroxide (Mg(OH)₂) and phosphoric acid (H₃PO₄) during the composting of pig manure can increase the content of TN in compost products.⁸⁴ Zhang *et al.* added calcium dihydrogen phosphate and magnesium sulfate to the compost raw materials, which can effectively reduce NH₃ by about 50%.⁶⁵ PO₄³⁻ and H₂PO₄⁻ are able to combine with NH₄⁺-N and Mg²⁺ in materials, and form complexes like NH₄MgPO₄·6H₂O and NH₄CaPO₄, which inhibit the conversion of NH₄⁺-N into NH₃-N, so as to reduce NH₃ emissions.⁸⁵ The ion reaction process can refer to eqn (1)–(3).



Moreover, $\text{Mg}(\text{OH})_2$ and H_3PO_4 have an effect on the VSCs emission reduction. Zhang *et al.* reported that the addition of $\text{Mg}(\text{OH})_2$ and H_3PO_4 reduced H_2S emissions by nearly 50%. They mainly reduce the VSCs emission by increasing the pH of the compost.⁶⁵



In addition, some surfactants have related deodorization research, such as rhamnolipid and β -cyclodextrin. Taking the latter as an example, various compounds can be embedded in the hydrophobic hollow structure of β -cyclodextrin. Stable complexes are then formed, reducing the evaporation of volatile materials. However, chemical agents also have their shortcomings. The use of chemical processes to remove odorous gases is very expensive.⁸⁶ If chemical methods are combined with other methods, a balance between the effect and price may be found. For example, if Fenton's reagent is used for the pretreatment of microbial inoculants, the ideal treatment effect may be achieved by using a small amount of chemical reagents and microbial inoculants.

3.2.3 Adsorbents. Natural or synthetic adsorbents with porous structure and high surface area can adsorb huge amounts of odors generated in compost. Some adsorbents can be effectively recycled and reused at the end of composting. The typical adsorbents mainly included zeolite,⁸⁷ biochar,⁸⁸ woody peat,⁶⁷ and medical stone.⁸⁹

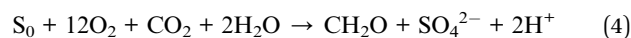
Among the many composting sorbents, most research has been on biochar. Steiner *et al.* mixed biochar with compost, which resulted in decreasing the NH_4^+ concentration, significantly reducing the NH_3 volatilization by about 64%, and reducing the nitrogen loss by up to 52%.⁹⁰ The addition of biochar will also increase the concentration of NO_3^- .^{91,92} The high ion exchange capacity of biochar makes it capable of adsorbing NH_4^+ in large quantities. The large surface area and porous structure of biochar facilitates its good adsorption capacity for absorbing NH_3 .^{93,94} Biochar can promote the growth of nitrifying microorganisms, which can reduce N_2O emissions and promote the conversion of ammonia to nitrate, thereby retaining the N element.^{95,96}

Steiner *et al.* found that the addition of biochar can reduce VSCs emissions by up to 71%.⁹⁰ According to current research, the inhibition of VSCs by biochar is mainly attributed to the porous structure of biochar, which improves the ventilation of the substrates. Biochar has a good adsorption effect on SO_4^{2-} and will affect the composting microbial communities.^{97,98} However, research on the effects of these functions of biochar on VSCs emissions from composting are lacking. The gas adsorption effect of biochar is related to the preparation temperature and raw materials. Compared with other materials and temperatures, the cornstalk biochar prepared at 500 °C has a larger specific surface area and adsorption capacity, and the adsorption effect is better.⁹⁹

The principle of zeolite's inhibition of odors is similar to that of biochar, including gas adsorption, ion exchange and the improvement of the microbial community.¹⁰⁰ The retention capacities of $\text{NH}_4^+/\text{NH}_3$ varied among different zeolite minerals. Several studies have shown that when natural zeolite is used for composting, the retention rate of $\text{NH}_4^+/\text{NH}_3$ can be increased by up to 50%.^{101,102} The advantage of biochar over other adsorbents is that it more obviously promotes the diversity of microbial communities.¹⁰³ The optimal ratio of the solid adsorbent to feces is determined by the type of adsorbent and feces. Too much filling will reduce the density of microorganisms, resulting in high ventilation, making the compost temperature unable to meet the requirements.

3.2.4 Microbial agents. As mentioned above, in addition to the main adsorption function, some adsorbents will affect the composting microbial community. This can also reduce the generation of odors. From the perspective of regulating the microbial community, the addition of microbial agents or inhibitors of the target microorganism metabolic activities will have a more direct effect. There are many studies on adding microbial agents to control odors in compost, such as lactic acid bacteria, *Bacillus*, *Saccharomyces* and others.^{104–106}

Due to the wide variety of microorganisms, the microbial inoculants that can be added to the compost are also numerous, and the mechanism of action varies. Some bacteria directly act on the N and S elements, and some bacteria have an inhibitory effect on the key bacteria that generate odors. Taking *Thiobacillus thiooparus* as a typical example of the former, *T. thiooparus* is one kind of sulfur-oxidizing bacteria, and has been used to control odors in biological filter treatment. However, it is rare in aerobic composting. Upon adding it to compost, the content of NO_3^- -N in the substrate increased significantly, which was 3–5 times higher than that of the control group. The cumulative amount of NH_3 emissions and TN loss were reduced by 21.86% and 26.39%, respectively.^{107,108} The changes in nitrogen illustrate that under the action of *T. thiooparus*, the nitrogen element was transformed into more stable nitrate nitrogen. The addition of *T. thiooparus* effectively reduced the cumulative emissions of H_2S , Me_2S , MeSH , and Me_2SS , and the TS loss by 33.24%, 81.24%, 32.70%, 54.22% and 54.24%, respectively.¹⁰⁸ *T. thiooparus* can promote the transformation from organic sulphur and elemental sulphur to sulphate, and effectively increased the proportion of available sulphur in the compost. The detailed reaction process is shown in chemical eqn (4).



Similar to *T. thiooparus*, many bacteria can transform NH_4^+ -N into relatively more stable organic nitrogen and NO_3^- -N, which can effectively reduce the amount of NH_3 released, such as ammonia oxidizing archaea, *Bacillus subtilis*, and others.^{109,110} Some strains of *Bacillus*, such as A strain *Pseudomonas aeruginosa* G12 and *Bacillus subtilis* M7-1, have the function of denitrification, which belongs to denitrifying reducing bacteria (DNB).^{111,112} DNB can inhibit the growth of sulfate-reducing bacteria (SRB), which has been widely used in water quality repair, corrosion prevention and other fields to reduce VSCs



Table 1 Summary of compost odor response to application of different control measures in studies

Technique types	Mechanism or main hypothesis	Specific measures	Effect on odor	Typical references
Increase oxygen (O ₂)	Promote NH ₃ oxidation; increase the ORP, inhibit the growth of SRB; maybe produce the blow-off effect	Different aeration rates from 0.1 to 0.3 L per (kg DM min)	High aeration rate reduces VSCs and NH ₃ by 30.7% and 51.33%, respectively	18
		Aeration rates from 100 to 1100 L h ⁻¹	Increase NH ₃ up to 600%	56
Adjust pH	NH ₃ : affect the NH ₄ ⁺ to NH ₃ ratio, a high pH will promote NH ₃ volatilization VSCs: H ₂ S is an acidic gas, alkaline environment reduces it production	Lower the pH from close to 9 to about 7.5	Reduce the cumulative NH ₃ emissions by 47.80%, but increase the H ₂ S emissions by 55%	108
Composting bulking agent	Adjust the water content of the substrate and provide organic matter; has a certain adsorption function; improve the sizes and numbers of inter-particle voids, providing air space	Addition of dry cornstalks at a mixing ratio of 4 : 1 (wet weight)	Reduce the VSCs emissions by 66.8%, the TN loss of the compost dropped from 45.8 to 24.9%	66
		Addition of dry cornstalks at a mixing ratio of 15% w/w	Reduced the total NH ₃ by 30.5%	74
Chemical agents (iron salt)	NH ₃ : FeCl ₃ being an effective flocculant and causing coagulation to occur VSCs: iron salts can react with dissolved sulfide to form elemental sulfur and sulfates	FeCl ₃ dosage in the raw materials was calculated to be 10% of the TN (by molar mass)	Reduce NH ₃ and H ₂ S emissions by 38% and 33%, respectively	68
Chemical agents (struvite)	NH ₃ : a chemical reaction occurred, NH ₄ ⁺ -N can be conserved in the form of struvite VSCs: increasing the pH of the compost	Mg(OH) ₂ and H ₃ PO ₄ dosage were calculated to be 10% of the TN (by molar mass)	Reduce NH ₃ and H ₂ S emissions by about 50%	65
Adsorbents	Adsorbents with porous structure and high surface area can adsorb huge amounts of odors generated in compost	Addition of biochar at a mixing ratio of 20% w/w	Reduce NH ₃ and VSCs emissions by 64% and 71%, respectively	90
Microbial agents	Affect the composting microbial community, or may inhibit odor-causing microorganisms	Inoculate 5% of laboratory-preserved strain <i>Thiobacillus thioparus</i> 1904	Reduce NH ₃ by 21.83%, reduce the cumulative emissions of H ₂ S, Me ₂ S, MeSH and Me ₂ SS by 33.24%, 81.24%, 32.70% and 54.22%, respectively	108
Mature compost	Can be used as a bulking agent to improve inter-particle voids; has adsorption function; rich in microorganisms, can affect the composting microbial community	Addition of mature compost at a mixing ratio of 10% w/w	Reducing the NH ₃ emission by 58.0%	120
		Addition of mature compost at a mixing ratio of 10% w/w	Reduce 65.1% H ₂ S emission	28

production.^{113,114} In other words, the addition of specific *Bacillus* strains can theoretically inhibit NH₃ and VSCs, but it lacks large numbers of practical experiments for demonstration. In addition to the direct addition of bacterial agents, electron donors (such as NO₃⁻-N and NO₂⁻-N) can promote the growth of DNB and inhibit SRB and VSCs.²⁷ In this respect, adding nitrifying bacteria theoretically also has the effect of inhibiting VSCs. Under the action of these bacteria, the concentration of NO₃⁻-N will increase and the concentration of NH₃ will decrease. In addition, it is effective in reducing the concentration of antibiotics.¹¹⁵

Compared with single strains, mixed strains and commercial compost special bacteria generally have a better odor treatment effect, such as the combination of *Bacillus* and ammonia-oxidizing bacteria. Their mechanism of suppressing odors in composting is also more complicated, and strain selection and ratio must be accurately designed.

3.2.5 Mature compost. The above chapter has introduced the emission reduction effect and mechanism of bulking agent, adsorbents and microbial inoculants on odors. Mature compost is the final product of the composting process, and has the



advantages of these three additives. Mature compost has been proposed to control odor emissions during the composting process, since it is an easily obtained material with porous, microbial-rich, and cost-efficient features. At present, mature compost has been widely applied in the control of odors in biological filters.^{116,117}

However, during the composting process, the performance of mature composts to control odor emissions remains controversial. Particularly, little is known about the effects in feces composting. Some research demonstrated that covering mature compost directly on the composting pile significantly reduced NH₃ emission with notable NH₄⁺ accumulation in the covered materials.^{118,119} Yang *et al.* mixed mature compost into the compost, reducing the NH₃ emission by 58.0%.¹²⁰ Mature compost can be used as a bulking agent to improve the inter-particle voids in the composite pile, thereby increasing the air permeability and adjusting the humidity of the compost substrate.⁷³ Due to its porous structure, it also has a good adsorption effect on odors. In addition, mature compost contains abundant microorganisms, which can accelerate the succession of microorganisms, thereby shortening the composting time.^{121,122} What is more, mature compost can create a suitable environment for microbial growth within the composting piles.¹²³

Yuan *et al.* covered the mature compost on the pile, reducing the H₂S emissions by 65.08%.¹²⁴ The mechanism of VSCs inhibition by the mature compost is similar to that of NH₃. There are many factors, such as adsorption, promotion of microorganisms, adjustment of the matrix porosity and humidity, that will all play a role. Some studies point out that mature compost will promote the growth of DNB, which will inhibit the proliferation of SRB.¹²⁵

Many studies have confirmed that mature compost can reduce odors. However, due to the complex mechanism, further research is still needed.^{18,126} Whether mature compost can effectively reduce odor emissions from feces composting and how it works is still unclear. The addition of mature compost generally requires about 5–10% w/w, which makes it more suitable for small-scale composting, such as rural toilet feces compost processes.

Various measures on odor control during composting studies are summarized in Table 1. The change in the compost pH is not feasible. The inhibitory effect of increasing the aeration rate on the odorous groups is still controversial, especially for NH₃. The addition of adsorbents and mature compost has a significant effect on odor suppression, and can basically achieve a 60% reduction effect on various odors. Composting bulking agent and some chemical agents can achieve about 50% reduction in odor emissions. The effect of microbial agents is not as good as other additives, which may be related to the microbial activity.

4. Conclusion & future perspectives

Aerobic composting is a reliable technique for converting manure into compost. This review summarizes several strategies for reducing odor emissions from manure composting.

These strategies can be used individually or in combination. In most cases, when the composting conditions have been adjusted to an appropriate range, there are still many odors. Therefore, additives are needed for further processing.

The composting bulking agent can effectively promote composting and reduce odor emissions. However, its addition ratio is limited by many factors, such as moisture content and C/N ratio, so the addition amount is also very limited. The addition of chemical agents and adsorbents helps reduce odor emissions during manure composting. However, for many composting plants, these additives are not cost-effective enough. Moreover, the mechanism of adsorbents to promote nitrogen conversion is not clear. The mechanism of microbial agents is complex, and more research and development of commercial compost inoculants are required. The mechanism of mature compost in the process of reducing compost odors is more complicated, which means that more research is needed, and it is more suitable for small-scale composting. The treatment mechanism of various additives and the treatment effect of different odors are also different. The composting plant needs to choose according to the characteristics of the compost. A further understanding of the mechanism, of which various additives reduce odors during composting, can help to find new and cost-effective additives.

In general, there are still some topics that need to be researched: (i) the mechanism of the adsorbents in promoting N conversion (ii) the mechanism of microbial agents in composting, including the effects on endogenous key microbial communities, (iii) research on the reduction of VSCs, especially VSCs other than H₂S, are often overlooked. (iv) New cost-effective additives.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are grateful for support from the National Key R&D Program of China (No. 2018YFC1903201), National Key R&D Program of China (No. 2019YFC0408204, No. 2018YFC0213605), Science and Technology Commission of Shanghai Municipality (19DZ1204702) and National Natural Science Foundation of China (52070126).

References

- 1 Y. Liu, R. N. Ma, D. Y. Li, C. R. Qi, L. N. Han, M. Chen, F. Fu, J. Yuan and G. X. Li, Effects of calcium magnesium phosphate fertilizer, biochar and spent mushroom substrate on compost maturity and gaseous emissions during pig manure composting, *J. Environ. Manage.*, 2020, **267**, 110649.
- 2 J. Kim, J. Kim and C. Lee, Anaerobic co-digestion of food waste, human feces, and toilet paper: methane potential and synergistic effect, *Fuel*, 2019, **248**, 189–195.



- 3 H. L. Wang, S. K. Zhu, B. Qu, Y. Zhang and B. Fan, Anaerobic treatment of source-separated domestic bio-wastes with an improved upflow solid reactor at a short HRT, *J. Environ. Sci.*, 2018, **66**, 255–264.
- 4 H. Y. Hwang, S. H. Kim, M. S. Kim, S. J. Park and C. H. Lee, Co-composting of chicken manure with organic wastes: characterization of gases emissions and compost quality, *Appl. Biol. Chem.*, 2020, **63**(1), 3.
- 5 X. Shang, H. Huang, K. Mei, F. Xia, Z. Chen, Y. Yang, R. A. Dahlgren, M. H. Zhang and X. L. Ji, Riverine nitrate source apportionment using dual stable isotopes in a drinking water source watershed of southeast China, *Sci. Total Environ.*, 2020, **724**, 137975.
- 6 G. F. O'Malley, The blood of my veins – mercury, Minamata and the soul of Japan, *Clin. Toxicol.*, 2017, **55**(8), 934–938.
- 7 G. Strom, A. Albihn, T. Jinnerot, S. Boqvist, A. Andersson-Djurfeldt, S. Sokerya, K. Osbjör, S. San, H. Davun and U. Magnusson, Manure management and public health: sanitary and socio-economic aspects among urban livestock-keepers in Cambodia, *Sci. Total Environ.*, 2018, **621**, 193–200.
- 8 D. W. Oguttu, A. Okullo, G. Bwire, P. Nsubuga and A. R. Ario, Cholera outbreak caused by drinking lake water contaminated with human faeces in Kaiso Village, Hoima District, Western Uganda, October 2015, *Infect. Dis. Poverty*, 2017, **6**(1), 146.
- 9 Y. R. Gu, S. Z. Shen, B. J. Han, X. L. Tian, F. X. Yang and K. Q. Zhang, Family livestock waste: an ignored pollutant resource of antibiotic resistance genes, *Ecotoxicol. Environ. Saf.*, 2020, **197**, 110567.
- 10 N. Udikovic-Kolic, F. Wichmann, N. A. Broderick and J. Handelsman, Bloom of resident antibiotic-resistant bacteria in soil following manure fertilization, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**(42), 15202–15207.
- 11 X. Wen, J. D. Mi, Y. Wang, B. H. Ma, Y. D. Zou, X. D. Liao, J. B. Liang and Y. B. Wu, Occurrence and contamination profiles of antibiotic resistance genes from swine manure to receiving environments in Guangdong Province southern China, *Ecotoxicol. Environ. Saf.*, 2019, **173**, 96–102.
- 12 N. Abila, Managing municipal wastes for energy generation in Nigeria, *Renewable Sustainable Energy Rev.*, 2014, **37**, 182–190.
- 13 A. Nandi, I. Megiddo, A. Ashok, A. Verma and R. Laxminarayan, Reduced burden of childhood diarrheal diseases through increased access to water and sanitation in India: a modeling analysis, *Soc. Sci. Med.*, 2017, **180**, 181–192.
- 14 E. A. Odey, Z. F. Li, X. Q. Zhou and L. Kalakodio, Fecal sludge management in developing urban centers: a review on the collection, treatment, and composting, *Environ. Sci. Pollut. Res.*, 2017, **24**(30), 23441–23452.
- 15 K. L. Hodge, J. W. Levis, J. F. DeCarolis and M. A. Barlaz, Systematic evaluation of industrial, commercial, and institutional food waste management strategies in the United States, *Environ. Sci. Technol.*, 2016, **50**(16), 8444–8452.
- 16 M. K. Awasthi, A. K. Pandey, P. S. Bundela, J. W. C. Wong, R. H. Li and Z. Q. Zhang, Co-composting of gelatin industry sludge combined with organic fraction of municipal solid waste and poultry waste employing zeolite mixed with enriched nitrifying bacterial consortium, *Bioresour. Technol.*, 2016, **213**, 181–189.
- 17 A. Saer, S. Lansing, N. H. Davitt and R. E. Graves, Life cycle assessment of a food waste composting system: environmental impact hotspots, *J. Cleaner Prod.*, 2013, **52**, 234–244.
- 18 H. Y. Zhang, G. X. Li, J. Gu, G. Q. Wang, Y. Y. Li and D. F. Zhang, Influence of aeration on volatile sulfur compounds (VSCs) and NH₃ emissions during aerobic composting of kitchen waste, *Waste Manage.*, 2016, **58**, 369–375.
- 19 C. Furlong, N. S. Rajapaksha, K. R. Butt and W. T. Gibson, Is composting worm availability the main barrier to large-scale adoption of worm-based organic waste processing technologies?, *J. Cleaner Prod.*, 2017, **164**, 1026–1033.
- 20 J. Jara-Samaniego, M. D. Perez-Murcia, M. A. Bustamante, A. Perez-Espinosa, C. Paredes, M. Lopez, D. B. Lopez-Lluch, I. Gavilanes-Teran and R. Moral, Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: suitability of the obtained composts for seedling production, *J. Cleaner Prod.*, 2017, **141**, 1349–1358.
- 21 Y. Zhao, Y. Q. Wei, Y. Zhang, X. Wen, B. D. Xi, X. Y. Zhao, X. Zhang and Z. M. Wei, Roles of composts in soil based on the assessment of humification degree of fulvic acids, *Ecol. Indic.*, 2017, **72**, 473–480.
- 22 J. Yuan, Y. Li, S. L. Chen, D. Y. Li, H. Tang, D. Chadwick, S. Y. Li, W. W. Li and G. X. Li, Effects of phosphogypsum, superphosphate, and dicyandiamide on gaseous emission and compost quality during sewage sludge composting, *Bioresour. Technol.*, 2018, **270**, 368–376.
- 23 M. K. Awasthi, Q. Wang, X. N. Ren, J. C. Zhao, H. Huang, S. K. Awasthi, A. H. Lahori, R. H. Li, L. N. Zhou and Z. Q. Zhang, Role of biochar amendment in mitigation of nitrogen loss and greenhouse gas emission during sewage sludge composting, *Bioresour. Technol.*, 2016, **219**, 270–280.
- 24 Z. Q. Shou, N. W. Zhu, H. P. Yuan, X. H. Dai and Y. W. Shen, Buffering phosphate mitigates ammonia emission in sewage sludge composting: enhanced organics removal coupled with microbial ammonium assimilation, *J. Cleaner Prod.*, 2019, **227**, 189–198.
- 25 R. Li, K. Xu, A. Ali, H. X. Deng, H. Z. Cai, Q. Wang, J. T. Pan, C. C. Chang, H. B. Liu and Z. Q. Zhang, Sulfur-aided composting facilitates ammonia release mitigation, endocrine disrupting chemicals degradation and biosolids stabilization, *Bioresour. Technol.*, 2020, **312**, 123653.
- 26 T. Jiang, G. X. Li, Q. Tang, X. G. Ma, G. Wang and F. Schuchardt, Effects of aeration method and aeration rate on greenhouse gas emissions during composting of pig feces in pilot scale, *J. Environ. Sci.*, 2015, **31**, 124–132.
- 27 B. Zhang, S. Y. Li, F. C. Michel, G. X. Li, D. F. Zhang and Y. Y. Li, Control of dimethyl sulfide and dimethyl



- disulfide odors during pig manure composting using nitrogen amendment, *Bioresour. Technol.*, 2017, **224**, 419–427.
- 28 J. Yuan, L. L. Du, S. Y. Li, F. Yang, Z. Y. Zhang and G. X. Li, Use of mature compost as filter media and the effect of packing depth on hydrogen sulfide removal from composting exhaust gases by biofiltration, *Environ. Sci. Pollut. Res.*, 2019, **26**(4), 3762–3770.
- 29 Y. L. Zhu, G. D. Zheng, D. Gao, T. B. Chen, F. K. Wu, M. J. Niu and K. H. Zou, Odor composition analysis and odor indicator selection during sewage sludge composting, *J. Air Waste Manage. Assoc.*, 2016, **66**(9), 930–940.
- 30 X. Wang, A. Selvam, M. T. Chan and J. W. C. Wong, Nitrogen conservation and acidity control during food wastes composting through struvite formation, *Bioresour. Technol.*, 2013, **147**, 17–22.
- 31 X. Wang, A. Selvam and J. W. C. Wong, Influence of lime on struvite formation and nitrogen conservation during food waste composting, *Bioresour. Technol.*, 2016, **217**, 227–232.
- 32 K. Maeda, D. Hanajima, S. Toyoda, N. Yoshida, R. Morioka and T. Osada, Microbiology of nitrogen cycle in animal manure compost, *Microb. Biotechnol.*, 2011, **4**(6), 700–709.
- 33 S. G. Wang and Y. Zeng, Ammonia emission mitigation in food waste composting: a review, *Bioresour. Technol.*, 2018, **248**, 13–19.
- 34 Y. Zeng, G. A. De, C. Ziebal, F. J. De Macedo and P. Dabert, Nitrification and microbiological evolution during aerobic treatment of municipal solid wastes, *Bioresour. Technol.*, 2012, **110**, 144–152.
- 35 R. Caceres, N. Coromina, K. Malinska, F. X. Martinez-Farre, M. Lopez, M. Sava and O. Marfa, Nitrification during extended co-composting of extreme mixtures of green waste and solid fraction of cattle slurry to obtain growing media, *Waste Manage.*, 2016, **58**, 118–125.
- 36 M. A. Chowdhury, A. de Neergaard and L. S. Jensen, Composting of solids separated from anaerobically digested animal manure: effect of different bulking agents and mixing ratios on emissions of greenhouse gases and ammonia, *Biosyst. Eng.*, 2014, **124**, 63–77.
- 37 R. Caceres, K. Malinska and O. Marfa, Nitrification within composting: a review, *Waste Manage.*, 2018, **72**, 119–137.
- 38 K. Wang, W. G. Li, X. K. Li and N. Q. Ren, Spatial nitrifications of microbial processes during composting of swine, cow and chicken manure, *Sci. Rep.*, 2015, **5**, 14932.
- 39 L. Q. Meng, W. G. Li, S. M. Zhang, C. D. Wu and L. Y. Lv, Feasibility of co-composting of sewage sludge, spent mushroom substrate and wheat straw, *Bioresour. Technol.*, 2017, **226**, 39–45.
- 40 A. Nigussie, T. W. Kuyper, S. Bruun and A. de Neergaard, Vermicomposting as a technology for reducing nitrogen loss and greenhouse gas emissions from small-scale composting, *J. Cleaner Prod.*, 2016, **139**, 429–439.
- 41 K. Tang, V. Baskaran and M. Nemati, Bacteria of the sulphur cycle: an overview of microbiology, biokinetics and their role in petroleum and mining industries, *Biochem. Eng. J.*, 2009, **44**(1), 73–94.
- 42 J. Bohacz, Changes in mineral forms of nitrogen and sulfur and enzymatic activities during composting of lignocellulosic waste and chicken feathers, *Environ. Sci. Pollut. Res.*, 2019, **26**(10), 10333–10342.
- 43 J. Bohacz and T. Kornilowicz-Kowalska, Changes in enzymatic activity in composts containing chicken feathers, *Bioresour. Technol.*, 2009, **100**(14), 3604–3612.
- 44 J. Chen, T. B. Chen, D. Gao, M. Lei, G. D. Zheng, H. T. Liu, S. L. Guo and L. Cai, Reducing H₂S production by O₂ feedback control during large-scale sewage sludge composting, *Waste Manage.*, 2011, **31**(1), 65–70.
- 45 J. Arogo, R. H. Zhang, G. L. Riskowski and D. L. Day, Hydrogen sulfide production from stored liquid swine manure: a laboratory study, *Trans. ASAE*, 2000, **43**(5), 1241–1245.
- 46 F. F. Xia, Y. Su, X. M. Wei, Y. H. He, Z. C. Wu, A. Ghulam and R. He, Diversity and activity of sulphur-oxidizing bacteria and sulphate-reducing bacteria in landfill cover soils, *Lett. Appl. Microbiol.*, 2014, **59**(1), 26–34.
- 47 H. Zhang, K. Zou, J. Yang, G. Li, Q. Yang and F. Zhang, Analysis of odor pollutants in kitchen waste composting, *Huanjing Kexue*, 2012, **33**(8), 2563–2568.
- 48 M. J. Higgins, Y. C. Chen, D. P. Yarosz, S. N. Murthy, N. A. Mass, D. Glindemann and J. T. Novak, Cycling of Volatile Organic Sulfur Compounds in Anaerobically Digested Biosolids and its Implications for Odors, *Water Environ. Res.*, 2006, **78**(3), 243–252.
- 49 B. Scaglia, V. Orzi, A. Artola, X. Font, E. Davoli, A. Sanchez and F. Adani, Odours and volatile organic compounds emitted from municipal solid waste at different stage of decomposition and relationship with biological stability, *Bioresour. Technol.*, 2011, **102**(7), 4638–4645.
- 50 H. Y. Zhang, F. Schuchardt, G. X. Li, J. B. Yang and Q. Y. Yang, Emission of volatile sulfur compounds during composting of municipal solid waste (MSW), *Waste Manage.*, 2013, **33**(4), 957–963.
- 51 G. D' Imporzano, F. Crivelli and F. Adani, Biological compost stability influences odor molecules production measured by electronic nose during food-waste high-rate composting, *Sci. Total Environ.*, 2008, **402**(2–3), 278–284.
- 52 L. Zhang, P. De Schryver, B. De Gussemme, W. De Muynck, N. Boon and W. Verstraete, Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review, *Water Res.*, 2008, **42**(1–2), 1–12.
- 53 J. Hobson and G. Yang, The ability of selected chemicals for suppressing odour development in rising mains, *Water Sci. Technol.*, 2000, **41**(6), 165–173.
- 54 Y. Chang, Y. T. Chang and H. J. Chen, A method for controlling hydrogen sulfide in water by adding solid phase oxygen, *Bioresour. Technol.*, 2007, **98**(2), 478–483.
- 55 Z. L. Han, F. Qi, H. Wang, B. Liu, X. Shen, C. Song, Z. Bao, X. Zhao, Y. Xu and D. Sun, Emission characteristics of volatile sulfur compounds (VSCs) from a municipal sewage sludge aerobic composting plant, *Waste Management*, 2018, **77**, 593–602.



- 56 A. de Guardia, C. Petiot, D. Rogeau and C. Druilhe, Influence of aeration rate on nitrogen dynamics during composting, *Waste Manage.*, 2008, **28**(3), 575–587.
- 57 K. H. Kim, R. Pal, J. W. Ahn and Y. H. Kim, Food decay and offensive odorants: a comparative analysis among three types of food, *Waste Manage.*, 2009, **28**(3), 575–587.
- 58 M. Chikae, R. Ikeda, K. Kerman, Y. Morita and E. Tamiya, Estimation of maturity of compost from food wastes and agro-residues by multiple regression analysis, *Bioresour. Technol.*, 2006, **97**(16), 1979–1985.
- 59 C. Lin, A negative-pressure aeration system for composting food wastes, *Bioresour. Technol.*, 2008, **99**(16), 7651–7656.
- 60 Y. Liang, J. J. Leonard and J. J. Feddes, A simulation model of ammonia volatilization in composting, *Trans. ASAE*, 2004, **47**(5), 1667–1680.
- 61 Y. Wang, S. J. Liu, W. T. Xue, H. Guo, X. R. Li, G. Y. Zuo, T. K. Zhao and H. M. Dong, The Characteristics of Carbon, Nitrogen and Sulfur Transformation During Cattle Manure Composting-Based on Different Aeration Strategies, *Int. J. Environ. Res. Public Health*, 2019, **16**(20), 3930.
- 62 S. Zhao, X. F. Yang, W. J. Zhang, J. Chang and D. S. Wang, Volatile sulfide compounds (VSCs) and ammonia emission characteristics and odor contribution in the process of municipal sludge composting, *J. Air Waste Manage. Assoc.*, 2019, **69**(11), 1368–1376.
- 63 S. Li, G. H. Huang, C. J. An and H. Yu, Effect of different buffer agents on in-vessel composting of food waste: Performance analysis and comparative study, *J. Environ. Sci. Health, Part A: Toxic/Hazard. Subst. Environ. Eng.*, 2013, **48**(7), 772–780.
- 64 R. Guo, G. X. Li, T. Jiang, F. Schuchardt, T. B. Chen, Y. Q. Zhao and Y. J. Shen, Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost, *Bioresour. Technol.*, 2012, **112**, 171–178.
- 65 H. Y. Zhang, G. X. Li, J. Yuan, B. Zang and Q. Y. Ying, Nitrogen fixation additive reducing emission of NH₃ and H₂S during composting of kitchen waste and cornstalk, *Trans. Chin. Soc. Agric. Eng.*, 2013, **29**(23), 173–178.
- 66 J. I. Chang and Y. J. Chen, Effects of bulking agents on food waste composting, *Bioresour. Technol.*, 2010, **101**(15), 5917–5924.
- 67 J. Yuan, D. F. Zhang, L. L. Du, F. Yang, G. X. Li and Y. Luo, Effect of Woody Peat as an Additive on Maturity and Gaseous Emissions During Pig Manure Composting, *Compost Sci. Util.*, 2019, **27**(2), 69–80.
- 68 J. Yuan, Q. Y. Yang, Z. Y. Zhang, G. X. Li, W. H. Luo and D. F. Zhang, Use of additive and pretreatment to control odors in municipal kitchen waste during aerobic composting, *J. Environ. Sci.*, 2015, **37**, 83–90.
- 69 F. Yang, G. X. Li, Q. Y. Yang and W. H. Luo, Effect of bulking agents on maturity and gaseous emissions during kitchen waste composting, *Chemosphere*, 2013, **93**(7), 1393–1399.
- 70 H. Y. Zhang, P. L. Lu, G. X. Li, W. Zhang, J. B. Yang, B. Zang and K. Wang, Effect of corn stalks addition on odors and leachate reduction during kitchen waste composting, *Trans. Chin. Soc. Agric. Eng.*, 2011, **27**(9), 248–252.
- 71 D. L. Elwell, H. M. Keener, M. C. Wiles, D. C. Borger and L. B. Willett, Odorous emissions and odor control in composting swine manure/sawdust mixes using continuous and intermittent aeration, *Trans. ASAE*, 2001, **44**(5), 1307–1316.
- 72 J. I. Chang and T. E. Hsu, Effects of compositions on food waste composting, *Bioresour. Technol.*, 2008, **99**(17), 8068–8074.
- 73 M. K. Iqbal, T. Shafiq and K. Ahmed, Characterization of bulking agents and its effects on physical properties of compost, *Bioresour. Technol.*, 2010, **101**(6), 1913–1919.
- 74 Y. Li, J. Yuan, G. X. Li, D. F. Zhang, G. Y. Wang, B. X. Zhang and X. Y. Gong, Use of additive to control odors and promote maturity of municipal kitchen waste during aerobic composting, *China Environ. Sci.*, 2017, **37**(3), 1031–1039.
- 75 H. A. Aziz, A. Omran and W. R. Zakaria, H₂O₂ Oxidation of Pre-Coagulated Semi Aerobic Leachate, *Int. J. Environ. Res.*, 2010, **4**(2), 209–216.
- 76 C. A. Wilson, C. T. Tanneru, S. Banjade, S. N. Murthy and J. T. Novak, Anaerobic digestion of raw and thermally hydrolyzed wastewater solids under various operational conditions, *Water Environ. Res.*, 2011, **83**(9), 815–825.
- 77 B. R. Dhar, E. Elbeshbishy, H. Hafez, G. Nakhla and M. B. Ray, Thermo-oxidative pretreatment of municipal waste activated sludge for volatile sulfur compounds removal and enhanced anaerobic digestion, *Chem. Eng. J.*, 2011, **174**(1), 166–174.
- 78 J. A. Smith and C. M. Carliell-Marquet, The digestibility of iron-dosed activated sludge, *Bioresour. Technol.*, 2008, **99**(18), 8585–8592.
- 79 D. P. Komilis, R. K. Ham and J. K. Park, Emission of volatile organic compounds during composting of municipal solid wastes, *Water Res.*, 2004, **38**(7), 1707–1714.
- 80 F. El-Gohary, M. Badawy, M. A. El-Khateeb and A. El-Kalliny, Integrated treatment of olive mill wastewater (OMW) by the combination of Fenton's reaction and anaerobic treatment, *J. Hazard. Mater.*, 2009, **162**(2–3), 1536–1541.
- 81 F. El-Gohary, A. Tawfik, M. Badawy and M. A. El-Khateeb, Potentials of anaerobic treatment for catalytically oxidized olive mill wastewater (OMW), *Bioresour. Technol.*, 2009, **100**(7), 2147–2154.
- 82 Y. Li, W. H. Luo, G. X. Li, K. Wang and X. Y. Gong, Performance of phosphogypsum and calcium magnesium phosphate fertilizer for nitrogen conservation in pig manure composting, *Bioresour. Technol.*, 2018, **250**, 53–59.
- 83 Y. K. Jeong and J. S. Kim, A new method for conservation of nitrogen in aerobic composting processes, *Bioresour. Technol.*, 2001, **79**(2), 129–133.
- 84 L. M. Ren, F. Schuchardt, Y. J. Shen, G. X. Li and C. P. Li, Impact of struvite crystallization on nitrogen losses during composting of pig manure and cornstalk, *Waste Manage.*, 2010, **30**(5), 885–892.
- 85 J. Wu, S. Z. He, G. X. Li, Z. H. Zhao, Y. Q. Wei, Z. Lin and D. Tao, Reducing ammonia and greenhouse gas emission with adding high levels of superphosphate fertilizer



- during composting, *Environ. Sci. Pollut. Res.*, 2019, **26**(30), 30921–30929.
- 86 S. Z. Ahammad, J. Gomes and T. R. Srekrishnan, Wastewater treatment for production of H₂S-free biogas, *J. Chem. Technol. Biotechnol.*, 2008, **83**(8), 1163–1169.
- 87 B. Madrini, S. Shibusawa, Y. Kojima and S. Hosaka, Effect of natural zeolite (clinoptilolite) on ammonia emissions of leftover food-rice hulls composting at the initial stage of the thermophilic process, *J. Agric. Meteorol.*, 2016, **72**(1), 12–19.
- 88 M. A. Sanchez-Monedero, M. L. Cayuela, A. Roig, K. Jindo, C. Mondini and N. Bolan, Role of biochar as an additive in organic waste composting, *Bioresour. Technol.*, 2018, **247**, 1155–1164.
- 89 Q. Wang, Z. Wang, M. K. Awasthi, Y. H. Jiang, R. H. Li, X. N. Ren, J. C. Zhao, F. Shen, M. J. Wang and Z. Q. Zhang, Evaluation of medical stone amendment for the reduction of nitrogen loss and bioavailability of heavy metals during pig manure composting, *Bioresour. Technol.*, 2016, **220**, 297–304.
- 90 C. Steiner, K. C. Das, N. Melear and D. Lakly, Reducing Nitrogen Loss during Poultry Litter Composting Using Biochar, *J. Environ. Qual.*, 2010, **39**(4), 1236–1242.
- 91 W. Liu, R. Huo, J. X. Xu, S. X. Liang, J. J. Li, T. K. Zhao and S. T. Wang, Effects of biochar on nitrogen transformation and heavy metals in sludge composting, *Bioresour. Technol.*, 2017, **235**, 43–49.
- 92 I. Lopez-Cano, A. Roig, M. L. Cayuela, J. A. Alburquerque and M. A. Sanchez-Monedero, Biochar improves N cycling during composting of olive mill wastes and sheep manure, *Waste Manage.*, 2016, **49**, 553–559.
- 93 M. Sanchez-Garcia, J. A. Alburquerque, M. A. Sanchez-Monedero, A. Roig and M. L. Cayuela, Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions, *Bioresour. Technol.*, 2015, **192**, 272–279.
- 94 K. Malinska, M. Zabochnicka-Swiatek and J. Dach, Effects of biochar amendment on ammonia emission during composting of sewage sludge, *Ecol. Eng.*, 2014, **71**, 474–478.
- 95 L. Zhang and X. Y. Sun, Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar, *Bioresour. Technol.*, 2014, **171**, 274–284.
- 96 W. Chen, X. D. Liao, Y. B. Wu, J. B. Liang, J. D. Mi, J. J. Huang, H. Zhang, Y. Wu, Z. F. Qiao, X. Li and Y. Wang, Effects of different types of biochar on methane and ammonia mitigation during layer manure composting, *Waste Manage.*, 2017, **61**, 506–515.
- 97 P. Godlewska, H. P. Schmidt, Y. S. Ok and P. Oleszczuk, Biochar for composting improvement and contaminants reduction. A review, *Bioresour. Technol.*, 2016, **246**, 193–202.
- 98 H. P. Wu, C. Lai, G. M. Zeng, J. Liang, J. Chen, J. J. Xu, J. Dai, X. D. Li, J. F. Liu, M. Chen, L. H. Lu, L. Hu and J. Wan, The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review, *Crit. Rev. Biotechnol.*, 2017, **37**(6), 754–764.
- 99 R. H. Li, Q. Wang, Z. Q. Zhang, G. J. Zhang, Z. H. Li, L. Wang and J. Z. Zheng, Nutrient transformation during aerobic composting of pig manure with biochar prepared at different temperatures, *Environ. Technol.*, 2015, **36**(7), 815–826.
- 100 S. Montalvo, C. Huilnir, R. Borja, E. Sanchez and C. Herrmann, Application of zeolites for biological treatment processes of solid wastes and wastewaters – a review, *Bioresour. Technol.*, 2020, **301**, 122808.
- 101 M. T. Chan, A. Selvam and J. W. C. Wong, Reducing nitrogen loss and salinity during ‘struvite’ food waste composting by zeolite amendment, *Bioresour. Technol.*, 2016, **200**, 838–844.
- 102 M. K. Awasthi, Q. Wang, H. Huang, X. N. Ren, A. H. Lahori, A. Mahar, A. Ali, F. Shen, R. H. Li and Z. Q. Zhang, Influence of zeolite and lime as additives on greenhouse gas emissions and maturity evolution during sewage sludge composting, *Bioresour. Technol.*, 2016, **216**, 172–181.
- 103 W. Liu, S. T. Wang, J. Zhang and T. Xu, Biochar influences the microbial community structure during tomato stalk composting with chicken manure, *Bioresour. Technol.*, 2014, **154**, 148–154.
- 104 M. Rastogi, M. Nandal and B. Khosla, Microbes as vital additives for solid waste composting, *Heliyon*, 2020, **6**(2), e03343.
- 105 O. J. Sanchez, D. A. Ospina and S. Montoya, Compost supplementation with nutrients and microorganisms in composting process, *Waste Manage.*, 2017, **69**, 136–153.
- 106 J. D. Harindintwali, J. L. Zhou and X. B. Yu, Lignocellulosic crop residue composting by cellulolytic nitrogen-fixing bacteria: a novel tool for environmental sustainability, *Sci. Total Environ.*, 2020, **715**, 136912.
- 107 W. J. Gu, F. B. Zhang, P. Z. Xu, S. H. Tang, K. Z. Xie, X. Huang and Q. Y. Huang, Effects of sulphur and *Thiobacillus thioparus* on cow manure aerobic composting, *Bioresour. Technol.*, 2011, **102**(11), 6259–6535.
- 108 W. J. Gu, W. Sun, Y. S. Lu, X. Li, P. Z. Xu, K. Z. Xie, L. L. Sun and H. T. Wu, Effect of *Thiobacillus thioparus* 1904 and sulphur addition on odour emission during aerobic composting, *Bioresour. Technol.*, 2018, **249**, 254–260.
- 109 K. Z. Xie, X. S. Jia, P. Z. Xu, X. Huang, W. J. Gu, F. B. Zhang, S. H. Yang and S. H. Tang, Improved composting of poultry feces via supplementation with ammonia oxidizing archaea, *Bioresour. Technol.*, 2012, **120**, 70–77.
- 110 L. B. Wan, X. T. Wang, C. Cong, J. B. Li, Y. P. Xu, X. Y. Li, F. Q. Hou, Y. Y. Wu and L. L. Wang, Effect of inoculating microorganisms in chicken manure composting with maize straw, *Bioresour. Technol.*, 2020, **301**, 122730.
- 111 Q. An, S. M. Deng, J. Xu, H. Y. Nan, Z. Li and J. L. Song, Simultaneous reduction of nitrate and Cr(VI) by *Pseudomonas aeruginosa* strain G12 in wastewater, *Ecotoxicol. Environ. Saf.*, 2020, **191**, 110001.
- 112 Q. S. Ma and Z. G. He, Screening and Characterization of Nitrite-Degrading Bacterial Isolates Using a Novel Culture Medium, *J. Ocean Univ. China*, 2020, **19**(1), 241–248.



- 113 F. Torun, B. Hostins, J. Teske, P. De Schryver, N. Boon and J. De Vrieze, Nitrate amendment to control sulphide accumulation in shrimp ponds, *Aquaculture*, 2020, **521**, 735010.
- 114 Z. S. Liang, L. Zhang, D. Wu, G. H. Chen and F. Jiang, Systematic evaluation of a dynamic sewer process model for prediction of odor formation and mitigation in large-scale pressurized sewers in Hong Kong, *Water Res.*, 2019, **154**, 94–103.
- 115 S. Abou-Elela and M. A. El-Khateeb, Performance evaluation of activated sludge process for treating pharmaceutical wastewater contaminated with β -lactam antibiotics, *J. Ind. Pollut. Control*, 2015, **31**(1), 1–5.
- 116 J. H. Hong and K. J. Park, Compost biofiltration of ammonia gas from bin composting, *Bioresour. Technol.*, 2005, **96**(6), 741–745.
- 117 C. Hort, S. Gracy, V. Platel and L. Moynault, A comparative study of two composts as filter media for the removal of gaseous reduced sulfur compounds (RSCs) by biofiltration: application at industrial scale, *Waste Manage.*, 2013, **33**(1), 18–25.
- 118 K. Maeda, R. Morioka and T. Osada, Effect of covering composting piles with mature compost on ammonia emission and microbial community structure of composting process, *J. Environ. Qual.*, 2009, **38**(2), 598–606.
- 119 W. H. Luo, J. Yuan, Y. M. Luo, G. X. Li, L. D. Nghiem and W. E. Price, Effects of mixing and covering with mature compost on gaseous emissions during composting, *Chemosphere*, 2014, **117**, 14–19.
- 120 F. Yang, Y. Li, Y. H. Han, W. T. Qian, G. X. Li and W. H. Luo, Performance of mature compost to control gaseous emissions in kitchen waste composting, *Sci. Total Environ.*, 2019, **657**, 262–269.
- 121 K. Kato and N. Miura, Effect of matured compost as a bulking and inoculating agent on the microbial community and maturity of cattle manure compost, *Bioresour. Technol.*, 2008, **99**(9), 3372–3380.
- 122 H. D. Zhang, J. N. Marchant-Forde and X. Y. Zhang, Effect of Cornstalk Biochar Immobilized Bacteria on Ammonia Reduction in Laying Hen Manure Composting, *Molecules*, 2020, **25**(7), 1560.
- 123 C. Scheutz, P. Kjeldsen and J. E. Bogner, Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions, *Waste Manage. Res.*, 2009, **27**(5), 409–455.
- 124 J. Yuan, D. F. Zhang and R. N. Ma, Effects of inoculation amount and application method on the biodying performance of municipal solid waste and the odor emissions produced, *Waste Manage.*, 2019, **93**, 91–99.
- 125 K. Wang, Y. Q. Wu, W. G. Li, C. D. Wu and Z. Q. Chen, Insight into effects of mature compost recycling on N_2O emission and denitrification genes in sludge composting, *Bioresour. Technol.*, 2018, **251**, 320–326.
- 126 C. Y. Chen, J. T. Kuo and Y. C. Chung, Effect of matured compost as an inoculating agent on odour removal and maturation of vegetable and fruit waste compost, *Environ. Technol.*, 2013, **34**(3), 313–320.

