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Reducing odor emissions from feces aerobic composting: additives

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Aerobic composting is a reliable technology for treating human and animal feces, and converting them into resources. Odor emissions in compost (mainly NH_3 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.

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

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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 (NH_3(l)) in the liquid phase, which combines one proton (H^+) to form NH_4^+. The NH_4^+/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^-, NH_4^+/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

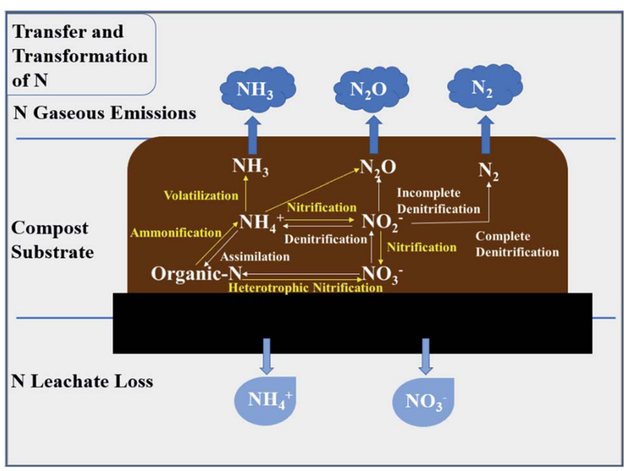

Fig. 1 Transfer and transformation of N in composting.

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]

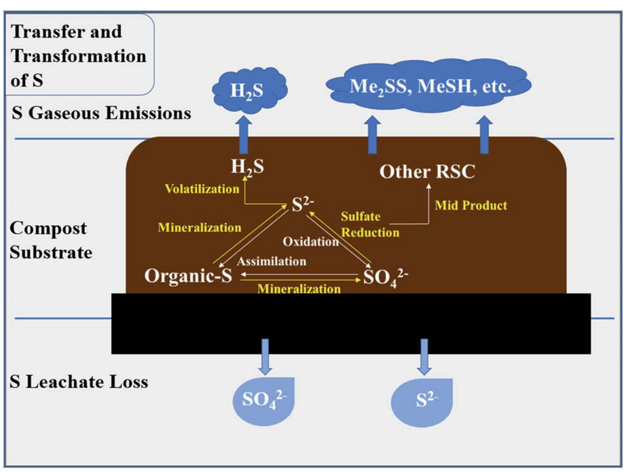

Fig. 2 Transfer and transformation of S in composting.

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 nitration 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 volatilization occurs at a high pH.[60] Contrary to NH_3, H_2S is an acidic gas; thus, the alkaline initial pH is the main factor for the reduction of H_2S emissions. An alkaline environment can keep H_2S mostly in the ionic forms, and can also absorb the generated H_2S.[61] Lowering the pH of the compost will reduce NH_3 production, but will increase the VSCs emissions.[62,63] Gu *et al.* also obtained similar results. After reducing the pH of compost, the cumulative NH_3 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 NH_3 emissions by 30.5%.[74] Cornstalks can absorb a considerable amount of NH_4^+/NH_3, 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 NH_3 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 NH_3 emissions is not so obvious.[70]

Compared with NH_3, 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 NH_3 and VSCs. Li *et al.* pointed out that due to the lower pH of the mushroom substrate, its inhibition of NH_3 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 ($FeCl_3$) has been widely used to remove NH_3 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 $FeCl_3$ to remove odors in composting is feasible. Yuan *et al.* added $FeCl_3$ to the compost to reduce NH_3 emissions by 38% compared to the control group.[68] The reduction of NH_3 emissions can be attributed to $FeCl_3$ being an effective flocculant, and causing coagulation to occur. H_2S 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 H_2S 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 ($NH_4MgPO_4\cdot6H_2O$) crystallization has been considered as an effective process for nitrogen conservation during composting. When magnesium and phosphorus salts are mixed with composting materials, NH_4^+-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 (H_3PO_4) 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 NH_3 by about 50%.[65] PO_4^{3-} and $H_2PO_4^-$ are able to combine with NH_4^+-N and Mg^{2+} in materials, and form complexes like $NH_4MgPO_4\cdot6H_2O$ and NH_4CaPO_4, which inhibit the conversion of NH_4^+-N into NH_3-N, so as to reduce NH_3 emissions.[85] The ion reaction process can refer to eqn (1)–(3).

Moreover, $Mg(OH)_2$ and H_3PO_4 have an effect on the VSCs emission reduction. Zhang *et al.* reported that the addition of $Mg(OH)_2$ 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]

$$NH_4^+ + Mg^{2+} + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O \quad (1)$$

$$NH_4^+ + Mg^{2+} + HPO_4^{2-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + H^+ \quad (2)$$

$$NH_4^+ + Mg^{2+} + HPO_4^{2-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + H^+ \quad (3)$$

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 NH_4^+/NH_3 varied among different zeolite minerals. Several studies have shown that when natural zeolite is used for composting, the retention rate of NH_4^+/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 thioparus* as a typical example of the former, *T. thioparus* 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. thioparus*, the nitrogen element was transformed into more stable nitrate nitrogen. The addition of *T. thioparus* 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. thioparus* 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).

$$S_0 + 12O_2 + CO_2 + 2H_2O \rightarrow CH_2O + SO_4^{2-} + 2H^+ \quad (4)$$

Similar to *T. thioparus*, 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_2S 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_2S 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_2S 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_3PO_4 dosage were calculated to be 10% of the TN (by molar mass)	Reduce NH_3 and H_2S 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 *Thiobacillus thioparus* 1904	Reduce NH_3 by 21.83%, reduce the cumulative emissions of H_2S, Me_2S, MeSH and Me_2SS 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_2S emission	28

production.[113,114] In other words, the addition of specific *Bacillus* strains can theoretically inhibit NH_3 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 NO_3^--N and NO_2^--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 NO_3^--N will increase and the concentration of NH_3 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 NH_3 emission with notable NH_4^+ accumulation in the covered materials.[118,119] Yang *et al.* mixed mature compost into the compost, reducing the NH_3 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 H_2S emissions by 65.08%.[124] The mechanism of VSCs inhibition by the mature compost is similar to that of NH_3. 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 NH_3. 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 H_2S, are often overlooked. (iv) New cost-effective additives.

Conflicts of interest

There are no conflicts to declare.

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