Mechanism and control strategy of ammonia and nitrous oxide during composting of municipal solid wastes

CHEN Yi-xiao1,a, LU Yi-ming1, MO Jin-tao1, PAN Jia-jing1 and ZHANG Jun1,b*

1College of Environmental Science and Engineering, Guilin University of Technology, 541006 Guilin, China

Abstract: Aerobic composting is an effective way to realize recycling of organic solid wastes. It is not only convenient for operation and management, but also can convert waste into organic fertilizer. However during the composting process, the nitrogen in the heap exists in the form of organic nitrogen, ammonium nitrogen, nitrate nitrogen and other forms and is transformed into each other. It is also a potential source of ammonia (NH₃) and nitrous oxide (N₂O), and it is closely related to the environmental problems such as haze pollution and greenhouse effect. Combining with the researches of domestic and foreign scholars, this paper summarizes the form transformation of nitrogen elements, the emission mechanism of NH₃ and N₂O, and the adjustment and control measures in the aerobic composting process of the organic solid wastes, and it prospects the research direction for aerobic composting of the organic solid wastes.

1 Introduction

In recent years, most of the organic solid wastes are randomly discarded or discharged into the environment, causing great negative impacts on the ecological environment. Municipal sludge is waste generated in the process of sewage treatment. If the sludge that has not been properly treated enters the environment directly, it will cause secondary pollution to the environment. Kitchen waste is easy to decay and deteriorate, and it is easy to breed bacteria. If placed improperly, it will have adverse effects on the social environment and human health. Aerobic composting is an effective way for minimization, hazard-free treatment and resourceful disposal of the organic solid wastes such as municipal sludge, kitchen wastes and livestock excrements. In the conditions of good ventilation and appropriate oxygen concentration, aerobic microorganisms multiply rapidly to degrade the organic solid wastes into organic fertilizers rich in humus and nutrient elements such as N, P, K [1-2]. However, the composting process is accompanied by NH₃ and N₂O emissions. NH₃ is an important precursor gas for the formation of PM₂.₅, and it is easily soluble in water. When the relative humidity is high, it can react with H₂SO₄, HNO₃ and HCl in the atmosphere to generate the secondary particles of ammonium salt, which is an important part of PM₂.₅ it can cause haze pollution to reduce the quality of the atmospheric environment, but also it threatens the human health [3]. N₂O is an important greenhouse gas that affects the radiation balance of the earth. Within 100 years, its single-molecule warming potential is 296 times of CO₂, which has a significant impact on the global greenhouse effect [4-5]. In summary, if the composting process is not properly controlled, the emitted NH₃ and N₂O will not only affect the global climate change, but also cause harm to various organisms, including the human health. Therefore, the research on reducing NH₃ and N₂O emissions during composting attracts more and more attention from scholars at home and abroad.

2 The form transformation of nitrogen elements during composting

The composting process is divided into the heating-up period, the high temperature period and the cooling and maturing period. Among them, the nitrogen elements mainly exist in the form of organic nitrogen, ammonium nitrogen and nitrate nitrogen [6], and they are transformed by mediating of microbial communities through ammonification, nitrification, denitrification and ammonia assimilation (Fig. 1).

Ammonification is a process in which organic nitrogen is decomposed by microorganisms to form NH₄+. It is divided into two periods: First, the organic nitrogen in the
waste pile is decomposed into amino compounds under the catalysis of proteases. And then, the amino compounds are transformed to be NH_{4}^{+} in the deamination process. The ammoniating reaction may occur throughout the composting cycle, and it is more intense in the heating stage, because the initial pile contains a large amount of organic nitrogen, and the temperature and pH are suitable at this time. The increase in temperature and pH will cause a large amount of NH_{4}^{+} to volatilize in the form of NH_{3}. In addition, NH_{4}^{+} can be oxidized to NO_{2}^{-} through nitrification, or it can be utilized by microorganisms to synthesize organic nitrogen as nutrients of ammonia assimilation [7-8].

Nitrification is a process in which NH_{4}^{+} is successively oxidized to NO_{3}^{-} by nitrifying bacteria. Ammonia oxidation is the first step of nitrification, which is divided into two periods: One is that NH_{3} is oxidized to NH_{2}OH under the action of ammonia monoxygenase; the other is that NH_{2}OH is oxidized to NO_{2}^{-} under the action of hydroxylamine oxidoreductase; and as an intermediate product of ammoniation, NH_{2}OH can further react with NO_{2}^{-} to form N_{2}O. The NO_{3}^{-} generated by nitrification can be absorbed and utilized by plants to synthesize nitrogen-containing organic matters, or it can be transformed to N_{2} through denitrification in anaerobic conditions [9-10].

Denitrification is the process in which NO_{3}^{-}, NO_{2}^{-}, NO and N_{2}O are successively reduced to N_{2} by denitrifying bacteria. The accumulation or compaction of the compost materials will prevent oxygen from entering the inside of the waste pile to form a local anaerobic environment and promote denitrification. Pseudomonas and paracoccus are typical aerobic denitrifying microorganisms, and their abundance is relatively less during the heating-up period of composting, and it will be gradually increased until the high temperature period and the cooling and maturing period [11-12].

Ammonia assimilation is a process in which α-ketoglutarate, an intermediate product of NH_{4}^{+} and carbon source metabolism, is catalyzed to synthesize glutamate and finally transformed to organic nitrogen. The synthesis of glutamate by NH_{4}^{+} can be achieved in two ways, one is that glutamate dehydrogenase catalyzes NH_{4}^{+} to directly react with α-ketoglutarate; the other is that glutamine synthetase acts together with glutamate synthetase, and it catalyzes NH_{4}^{+} to react with α-ketoglutarate and glutamine [13-14].

3 The emission mechanism of NH_{3} and N_{2}O during composting

The organic nitrogen in the waste pile undergoes ammoniating to form NH_{4}^{+}. As the temperature and the pH increase, NH_{4}^{+} is quickly transformed to NH_{3} which accelerates the emission of NH_{3}. Therefore, the high temperature period is the main period of NH_{3} volatilization during the composting process. When the temperature of the waste pile is reduced to the air temperature, the composting enters the maturing period. At this time, the content of NH_{4}^{+} decreases and the volatilization rate of NH_{3} also decreases due to the nitrification and the ammonia assimilation of NH_{4}^{+} as well as the continuous volatilization of NH_{3} [15-16].

In the composting process, both the nitrification of NH_{4}^{+} and the denitrification of NO_{3}^{-} will cause emission of N_{2}O. Maeda et al. [17] use the priority point value (SP), to study the N_{2}O emission mechanism of the cattle manure composting process. The results show that the SP value of N_{2}O emission in the initial stage of composting is 0 to 12, and the N_{2}O emission reaches the peak after the turning over the pile, the corresponding SP value is 0 to 5, while the SP value of N_{2}O emitted by nitrification is about 33, and the SP value of N_{2}O emitted by denitrification is about 0, which indicates that N_{2}O can come from both nitrification and denitrification, and denitrification is the main way to produce N_{2}O during the composting process. The researches of Ge et al. [11] show that, during the compost heating-up period and the high temperature period, N_{2}O is mainly emitted through the nitrification process led by ammonia oxidizing bacteria; when entering the cooling and maturing period, N_{2}O is mainly emitted through the denitrification process of ammonia oxidizing bacteria and denitrifying bacteria.

4 The reduction measures of NH_{3} and N_{2}O during composting

The initial characteristics of compost material such as temperature, pH, and moisture content significantly affect the carbon and nitrogen metabolism, and then affect the production and emission of NH_{3} and N_{2}O during the composting process. The biochemical reactions in aerobic composting are generally manifested by temperature changes. pH is not only related to the life activities of microorganisms, but also closely related to the existence of ammonium nitrogen [18]. The moisture content of the compost material is generally 50% to 70%, which mainly affects the diffusion of O_{2} in the waste pile, thereby indirectly affects the emission of NH_{3} and N_{2}O during the composting process [19]. Too high water content is not conducive to the diffusion of O_{2} in the waste pile, which weakens the mineralization of organic nitrogen thus reducing the emission of NH_{3} [20]. When the moisture content of the material reaches more than 60%, N_{2} is formed mainly by denitrification of nitrogen elements, so that the emission of N_{2}O is reduced [21]. Therefore, it is possible to reduce the emission of NH_{3} and N_{2}O during the composting process by adjusting and controlling the moisture content of material. For raw materials with low moisture content, it can be adjusted by adding water. When the raw material has a high moisture content, auxiliary materials such as straw and sawdust can be added.

Ventilation conditions have an important impact on the emissions of NH_{3} and N_{2}O during composting. Turning the pile will increase the O_{2} concentration in the pile, thereby promoting the mineralization of organic nitrogen and increasing the volatilization of NH_{3} [22]. It is generally believed that the amount of ammonia volatilization is positively correlated with the frequency of dumping [23]. Turn over the pile to homogenize the material, and the NO_{3}^{-} inside the pile body undergoes denitrification to generate N_{2}O, thereby increasing N_{2}O
emissions[24]. Zhao et al. [25] investigate the effect of turning frequency on greenhouse gas and ammonia emissions during the composting process of pig manure strips, and the results show that the increasing of turnover frequency has increased greenhouse gas and ammonia emissions. The intermittent ventilation method has a good emission reduction effect on NH3 and N2O generated during the composting process. Zhang et al. [26] adopt three intermittent ventilation methods to carry out the composting experiment, and the results show that, the emission of NH3 is the least after a 20-minute stop for every 40 minutes of ventilation. Ma et al. [27] find that, the intermittent ventilation method of a 10-minute stop for every 10 minutes of ventilation can reduce the emission of N2O by 47.10%.

Adding conditioners is an effective strategy to reduce NH3 and N2O emissions during composting. Physical additives have abundant pore structures and negative charge adsorption sites, which can adsorb NH3 and NH4+, and it can reduce the abundance of gases related to N2O production and increase the abundance of gases related to N2O reduction, so that N2O emissions such as biochar, medical stone, bentonite, etc. are reduced [18]. Biochar reduces NH3 emissions by 28.30~74.32% and N2O emissions by 79.51~81.10% [28]; while medical stone reduces NH3 emissions by 38.20~78.50% and N2O emissions by 46.60~82.40% [29]. Chemical additives can reduce NH3 emissions by lowering the pH of the material, fixing NH4+ or reacting with NH3 [30]. When Lei et al. [31] add phosphogypsum, the NH3 emissions are reduced by 59.74%, while the N2O emissions are increased by 8.15%. This may be the reason that the chemical additives reduce the pH of the material and inhibit activity of the N2O reductase. In addition, the promotion of nitrification or assimilation of NH4+ through biological additives can reduce the NH3 emissions by 10.20% to 42.80% [30]. Jiang et al. [32] find that, when the addition amount of dicyandiamide was higher than 2.5%, the nitrification is inhibited, and the N2O emissions is reduced by 77%.

5 Conclusions
The reduction measures of NH3 and N2O emission during the composting process include the conditioning of material properties, the optimization of process conditions, the addition of conditioners, etc. At present, the emission reduction mechanism of NH3 and N2O emissions during the composting process still needs to be explored. This is because the adjustment and control measures will affect multiple factors at the same time, and the trade-off phenomenon may even occur. Therefore, in the future, it is necessary to increase research on the influencing factors of composting effect, and further narrow the scope of the most suitable conditions for operation. In addition, on the basis of adjusting the material properties and optimizing the process conditions, the use of additives shall be combined to realize the coordinated emission reduction of NH3 and N2O during the composting process. Aerobic composting can not only reduce environmental pressure, but also make organic solid waste resources. With the continuous deepening of research, the improvement of composting technology will make aerobic composting more environmentally friendly, more efficient, and more suitable for large-scale composting.

References
1. Bai, M., Impraim, R., Coates, T.W., et al. (2020) Lignite effects on NH3, N2O, CO2 and CH4 emissions during composting of manure. Journal of Environmental Management, 271:110960.
2. He, X., Yin, H., Fang, C., et al. (2021) Metagenomic and q-PCR analysis reveals the effect of powder bamboo biochar on nitrous oxide and ammonia emissions during aerobic composting. Bioresource Technology, 323:124567.
3. Jiang, B.F., Xia, D.H. (2017) Role identification of NH3 in atmospheric secondary new particle formation in haze occurrence of China. Atmospheric Environment, 163:107-117.
4. Ma, S., Xiong, J., Cui, R., et al. (2020) Effects of intermittent aeration on greenhouse gas emissions and bacterial community succession during large-scale membrane-covered aerobic composting. Journal of Cleaner Production, 266:121551.
5. Wu, W.X., Li, L.J., Lv, H.H., Wang, C., Deng, H. (2012) Mechanisms of nitrous oxide emission during livestock manure aerobic composting. Chinese Journal of Applied Ecology, 23(06):1704-1712.
6. Shi, M.Z., Zhao, Y., Zhu L.J., Song, X.Y., Tang, Y., Qi, H.S., Cao, H.G., Wei, Z.M. (2020) Denitrification during composting: Biochemistry, implication and perspective. International Biodeterioration & Biodegradation, 153:105043.
7. Huang, Y., Li, D.Y., Wang, L., et al. (2019) Decreased enzyme activities, ammonification rate and ammonifiers contribute to higher nitrogen retention in hyperthermophilic pretreatment composting. Bioresource Technology, 272:521-528.
8. Ma, C., Hu, B., Liu, F.Y., Zhang, H.Z., Wei, M.B., Zhao J.H. (2019) Review on changes of microorganisms and enzyme activities during aerobic composting of organic waste. Environmental Engineering, 37(09):159-164+187.
9. Caceres, R., Malinska, K., Marfa, O. (2018) Nitrification within composting: A review. Waste Management, 72:119-137.
10. Maeda, K., Dai, H., Toyoda, S., et al. (2011) Microbiology of nitrogen cycle in animal manure compost. Microbial Biotechnology, 4(6):700-709.
11. Ge, J.Y., Huang, G.Q., Li, J.B., et al. (2018) Multivariate and multiscale approaches for interpreting the mechanisms of nitrous oxide emission during pig manure-wheat straw aerobic composting. Environmental Science & Technology, 52(15):8408-8418.
12. Fukumoto,Y., Suzuki,K., Kuroda, K., et al. (2011) Effects of struvite formation and nitratation promotion on nitrogenous emissions such as NH3,
13. Wang, S.J., Zeng, Y. (2018) Ammonia emission mitigation in food waste composting: A review. Bioresource Technology, 248:13-19.

14. Shou, Z.Q., Zhu, N.W., Yuan, H.P., Dai, X.H., Shen, Y.W. (2019) Buffering phosphate mitigates ammonia emission in sewage sludge composting: Enhanced organics removal coupled with microbial ammonium assimilation. Journal of Cleaner Production, 227:189-198.

15. Guo, H.H., Gua, J., Wang, X.J., et al. (2020) Microbial driven reduction of N₂O and NH₃ emissions during composting: Effects of bamboo charcoal and bamboo vinegar. Journal of Hazardous Materials, 390:121292.

16. Meng, L.Q., Li, W.J., Zhang, S.M., et al. (2016) Effect of different extra carbon sources on nitrogen loss control and the change of bacterial populations in sewage sludge composting. Ecological Engineering, 94:238-243.

17. Maeda, K., Toyoda, S., Philippot, L., et al. (2017) Relative contribution of nirK- and nirS- bacterial denitrifiers as well as fungal denitrifiers to nitrous oxide production from dairy manure compost. Environmental Science & Technology, 51:14083-14091.

18. Liao, L.M., Zhao, L.J., Lu, Y.X., Chen, M.L., Su, C.Y. (2019) Nitrogen transformation and loss control strategy during composting of municipal solid wastes. Environmental Science & Technology, 39(02):133-137.

19. Cao, Y.B., Zhang, L., Wang, X., et al. (2020) Synergistic mitigation of ammonia and greenhouse gas emissions during livestock waste composting. Journal of Agro-Environment Science, 39(4): 923-932.

20. Fan, H., Liao, J., Abass, O.K., et al. (2019) Effects of bulking material types on water consumption and pollutant degradation in composting process with controlled addition of different liquid manures. Bioresource Technology, 288:121517.

21. Chen, H., Wang J.Y., Tian, X.F., et al. (2019) Effects of different water content and C/N coupling on greenhouse gas emissions during donkey dung composting. Ecology and Environmental Sciences, 28(2):341-347.

22. Pardo, G., Moral, R., Aguilera, E., et al. (2015) Gaseous emissions from management of solid waste: A systematic review. Global Change Biology, 21(3):1313-1327.

23. Cao, Y.B., Xing, X.X., Bai, Z.H., et al. (2018) Review on ammonia emission mitigation techniques of crop - livestock production system. Scientia Agricultura Sinica, 51(3):566-580.

24. Jiang, T., Frank, S., Li, G.X. (2011) Effect of turning and covering on greenhouse gas and ammonia emissions during the winter composting. Transactions of the CSÆ, 27(10):212-217.

25. Zhao, C.Y., Li, H.M., Wei, Y.S., et al. (2014) Effects of turning frequency on emission of greenhouse gas and ammonia during swine manure windrow composting. Environmental Science, 35(2):533-540.

26. Zhang, H., Wang, G.Q., Gu, J., et al. (2017) Influence of ventilation on H₂S and NH₃ emission during kitchen waste composting. Journal of China Agricultural University, 22(12):124-130.

27. Ma, S., Xiong, J., Cui, R., et al. (2020) Effects of intermittent aeration on greenhouse gas emissions and bacterial community succession during large-scale membrane-covered aerobic composting. Journal of Cleaner Production, 266:121551.

28. Wang, C., Lu, H., Dong, D., et al. (2013) Insight into the effects of biochar on manure composting: Evidence supporting the relationship between N₂O emission and denitrifying community. Environmental Science & Technology, 47(13):7341-7349.

29. Awasthi, M.K., Wang, Q., Awasthi, S.K., Wang, M., Chen, H., Ren, X., Zhao, J., Zhang, Z. (2018) Influence of medical stone amendment on gaseous emissions, microbial biomass and abundance of ammonia oxidizing bacteria genes during biosolidscomposting. Bioresource Technology, 247:970–979.

30. Cao, Y., Wang, X., Bai, Z., et al. (2019) Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: A meta-analysis. Journal of Cleaner Production, 235:626-635.

31. Lei, L., Gu, J., Wang, X., et al. (2020) Effects of phosphogypsum and medical stone on nitrogen transformation, nitrogen functional genes, and bacterial community during aerobic composting. Science of The Total Environment, 753(9-10):141746.

32. Jiang, T., Ma, X., Tang, Q., et al. (2016) Combined use of nitrification inhibitor and struvite crystallization to reduce the NH₃ and N₂O emissions during composting. Bioresource Technology, 217:210-218.