SHS Web of Conferences **163**, 04033 (2023) https://doi.org/10.1051/shsconf/202316304033
ICSSED 2023

Research progress of biochar on nitrous oxide emissions from soil and its influencing mechanism

Wang Zhiwei[1a] ; Wei Yu[1] ; Chen Feng[2] ; Zhang Shuyong[3] ; Liu Hongyuan[2*b]

[1] Shandong Territorial Ecological Restoration Center, Jinan 250014, China; [2] Shandong Academy of Agricultural Sciences, Jinan 250100, China; [3] Agricultural Technology Extension Center of Yutai County, Jining 272300, Shandong Province, China

Abstract: Farmland soil is one of the important sources of N_2O emission. How to reduce the emission of N_2O from farmland soil is an important issue in the study of global climate change research the problem. The addition of biochar has been proved to be one of the means to improve soil and reduce the N_2O emission of farmland soil, but the underlying mechanism is unclear. In this paper, the effects of biochar on soil physicochemical properties and soil N_2O emission were reviewed. It is suggested that future studies on N_2O emission from biochar should also focus on soil aggregate size and aging of biochar for the application of biochar provide ideas and references.

1 Introduction

Nitrous oxide (N_2O) is not only one of the three major greenhouse gases, but also indirectly destroys the ozone layer. The N_2O emission from farmland accounts for 60% of the global total N_2O emission[1], which is mainly caused by the large amount of nitrogen fertilizer application in farmland, and China is one of the countries with the highest nitrogen application rate in the world. Therefore, how to reduce farmland soil N_2O emission has become a research hotspot.

Biochar is a kind of solid black substance with very high carbon content, which is not easy to decompose and is highly aromatic, which is produced by high temperature and slow heat carbonization of biomass under partial or complete hypoxia conditions. In recent years, researchers have attached great importance to the effect of biochar applied into soil on soil N_2O emission. Biochar affects N_2O emission by affecting soil physical and chemical properties, soil structure and microbial activities related to nitrogen migration and transformation in soil. However, the specific mechanism has not been unified and systematic. Therefore, this paper briefly summarized the effects of biochar addition on soil physicochemical properties and farmland N_2O emission and related mechanisms, and looked forward to the future theoretical research direction of the effects of biochar on soil N_2O emission, in order to provide reference for the feasibility of application of biochar to reduce farmland soil N_2O emission.

2 Effects of biochar on N_2O emission from farmland soil

A large number of studies have shown that adding biochar can significantly reduce soil N_2O emission. Studies have found that in the winter wheat-summer corn rotation system in Dezhou, Shandong province, the addition of 4.5-13.5 t/hm^2 biochar treatment reduces soil N_2O emission, up to 33.3%-62.2%[2]. The explanation given by the authors is that adding biochar can increase the pH value of soil, thus increase the activity of N_2O reductase (nosZ), and accelerate the conversion of N_2O to N_2. At the same time, it can inhibit the enzyme activity of NO- 3 and NO- 2 converting to N_2O, and reduce the production of N_2O in denitrification. The application of biochar can increase the permeability of soil and promote the diffusion of O_2 in soil, which is conducive to organic matter using N_2O to produce abiotic reaction to reduce the emission of N_2O. In addition, biochar can absorb and fix ammonium nitrogen in soil, reduce the substrate of denitrification, and inhibit the emission of soil N_2O.

The addition of biochar to soil will not necessarily lead to the reduction of soil N_2O emission. Since biochar itself contains NH+ 4 and NO- 3, increasing the reaction substrate of nitrification and denitrification will lead to the increase of soil N_2O emission. If biochar introduces too many easy components, especially if biochar is mixed with nitrogen-rich fertilizer, it will significantly increase soil N_2O emission.

In addition, other studies have shown that the application of biochar has no significant effect on soil N_2O emission. Yanai et al. believed that the addition of biochar would not significantly affect soil N_2O emission if soil moisture did not change[3]. In addition, Liu et al.[2]

[a]E-mail：318737186@qq.com
*bCorresponding author: saasliuhongyuan@163.com

found that low concentration of biochar had no significant effect on soil N_2O emission. The reason may be that the low concentration of biochar does not significantly change the soil physical and chemical properties and microbial activities, or the soil is not sensitive to the response of biochar due to the types or years of biochar added.

It can be seen that there are many studies on the effect of biochar addition on soil N_2O emission at present. However, due to the inconsistency of field experiment conditions and management measures, soil N_2O emission has different response effects to biochar application. Therefore, it is a very important task to systematically explore the mechanism of biochar's influence on soil N_2O emission.

3 Response mechanism of soil to biochar application

3.1 Effects of biochar on soil physicochemical properties

Most of the studies showed that the addition of biochar reduced soil N_2O emission through the influence of soil physicochemical properties. Biochar has special microstructure, which makes it maintain strong stability. Biochar can increase soil specific surface area, soil aeration and porosity, reduce soil hardness, and promote the formation of soil aggregates. Laird et al.[4] found that the application of biochar can significantly increase soil water holding capacity and soil porosity, and thus reduce soil N_2O emission, especially on sandy soil with poor water holding capacity. At the same time, biochar itself is alkaline, and the application of biochar can improve the pH value to reduce the microbial activity in neutral or acidic environment, and reduce the emission of soil N_2O. In addition, due to its unique porous structure, biochar also has a strong adsorption capacity, which can absorb soil inorganic nitrogen and other water-soluble salt ions, and has the ability to maintain fertilizer and reduce nitrogen loss. In conclusion, biochar can affect soil N_2O emission by adsorption and retention of inorganic nitrogen or by influencing the reaction processes of nitrification and denitrification.

Biochar contains some active carbon, which provides sufficient carbon source for microorganisms after application into the soil, can promote the growth and reproduction of microorganisms, and improve microbial activity. At the same time, the application of biochar into soil can increase the soil organic carbon content and the soil carbon-nitrogen ratio (C/N)[5]. Therefore, biochar can weaken nitrification and denitrification, thus reducing soil N_2O emission.

But there are other studies that suggest otherwise. Due to the black color of biochar and its good heat absorption, the application of biochar can increase soil temperature, and the increase of soil temperature can increase soil N_2O emission. Every 2 ℃ increase of soil temperature, soil N_2O emission will increase by 10.1%[6]. In addition, biochar can affect soil N_2O emission by changing soil moisture. Yanai et al.[3] found that when soil water content was 64%-78%, biochar could significantly reduce soil N_2O emission. When soil water content was 83%, biochar could significantly increase soil N_2O emission. When soil moisture content is high, aerobic microbial activities can be inhibited, thus reducing soil N_2O emission. However, when soil moisture content reaches a very high level, soil microorganisms will multiply in the water, thus causing more nitrogen fixation, and finally increasing the emission of N_2O. Therefore, to reduce soil N_2O emission by adding biochar, we should not only pay attention to the application amount of biochar, but also comprehensively consider the application environment.

3.2 Effects of biochar on soil nitrogen cycl-related microorganisms

Microorganisms related to soil nitrification and denitrification will be affected by changes in soil environment, thus affecting soil N_2O emission. In nitrification, ammonia oxidizing bacteria (AOB) and ammonia oxidizing archaea (AOA) are mainly used to complete the oxidation process of ammonia (NH_3) and control the production of N_2O. Previous studies have shown that, adding biochar to soil can increase the abundance of ammonia-oxidizing bacteria in soil by increasing soil pH value, thus improving the nitrification rate of soil. The porosity of biochar enables it to have strong adsorption capacity[7]. After the adsorption of phenolic compounds by biochar, the growth of nitrifying bacteria is promoted, thus indirectly promoting the nitrification of soil[8].

Nitrate reductase gene (narG), as a functional marker of denitrifying bacteria in denitrification, dominates the catalytic reduction process of NO- 3 to NO- 2. The conversion of nitrite to nitrogen oxide ($NO_2 \rightarrow NO$) catalyzed by nitrite reductase is the most critical step, and the most important functional marker genes in this process are nirK and nirS genes. The reduction of N_2O to N_2 catalyzed by nitrous oxide reductase is also considered very important. The inhibition of this process will be conducive to the production of nitrous oxide. The functional marker gene of this process is nosZ gene. Studying the ratio of N_2O/N_2 produced in denitrification process and its influencing factors is the key to solve the response mechanism of soil N_2O emission to biochar, and can provide a necessary theoretical basis for improving soil nitrogen use efficiency and reducing soil N_2O emission. Some studies believe that biochar contains some alkaline ash, which can inhibit denitrifying nitrate reductase, nitrite reductase and promote the activity of nitrous oxide reductase, thus reducing the production of N_2O[9]. Studies have shown that the main factors affecting denitrification are organic matter and nitrate content rather than oxygen content, which is because many microorganisms have periplasmic nitrate reductase (Nap)[10]. Nitrification and denitrification often have coupling effects, which jointly affect the emission of N_2O. At the same time, a wide variety of bacteria and some archaea, fungi and actinomyces have been found to participate in denitrification in more than 80 genera[11].

In addition, biochar can affect soil microbial activity and soil N_2O emission through other ways. Biochar can provide favorable conditions for the growth and reproduction of nitrogen-fixing microorganisms, thus further inducing nitrogen fixation. Xu et al.[12] found that for soil with high organic matter and sufficient nitrogen, inert biochar with relatively high temperature should be used to reduce soil N_2O emission mainly by the nature of biochar itself. Biochar, due to its own production and materials, may also produce some substances harmful to soil, thus inhibiting nitrification and denitrification.

3.3 Effects of biochar on soil aggregate structure

Biochar is thought to promote the formation of large aggregates in soil, which act as a binder to hold soil minerals together. However, some studies[13] found that the binding effect of biochar was not significant in alkaline soil. Similarly, Zhang et al.[14] did not observe the binding effect of biochar on soil minerals. This may be due to the large porosity of the soil and the strong leaching effect of the soil leading to the serious loss of biochar, which could not exert the binding effect of biochar, or it may be due to the disintegration of soil large aggregates. The dynamic changes of soil aggregates with time after application of biochar should be studied to determine the causes. In addition, although biochar can be used as a binder, this mechanism may be more important at the scale of microaggregates.

The influence of biochar on soil aggregates will certainly affect soil N_2O emission through this approach. Previous studies have found[15] that soil N_2O emission increases with the increase of soil aggregates and grain size, which indicates that the change of microaggregate composition by biochar may be one of the reasons for inhibiting the production of soil N_2O. In addition, other studies[16] found that the nitrification, denitrification and total bacterial communities in microaggregates were higher than those in large aggregates, indicating that microaggregates are potential hot spots for N_2O production.

3.4 Effects of biochar on soil nitrogen balance

Most studies show that biochar has a significant inhibitory effect on soil N_2O. However, biochar can reduce soil N_2O emission, but will it increase other nitrogen loss pathways? Does it affect soil nitrogen balance? There has been little attention to this in previous studies. Therefore, paying attention to the effect of biochar on soil nitrogen balance is the basis for the future application of biochar, and is another important reflection of its own value. Nitrogen surplus is an important content to evaluate soil nitrogen balance, and is the best index to evaluate nitrogen input and output as well as environmental impact changes[17]. Nitrogen surplus is the amount of soil nitrogen that a production unit can establish its own nitrogen cycle without causing the loss of soil, water and gas nitrogen, calculated through years of experimental research. Studies have shown that the recommended nitrogen surplus under wheat-maize rotation system in North China is 80 kg N/hm^2[18]. In addition, nitrogen loss refers to the nitrogen content of soil nitrogen into water and gas, which is an important evaluation index of soil nitrogen balance. Combined with nitrogen surplus amount, soil nitrogen balance can be effectively judged. Analysis of nitrogen surplus has been widely used to promote sustainable nutrition management at the smallholder farm, regional, national and even global levels[19]. These studies contribute to agricultural management in the field and help limit environmental degradation without sacrificing yields. Previous studies such as site-point nitrogen management, balanced nitrogen fertilization, and integrated nitrogen management have been shown to be effective in increasing nitrogen utilization and reducing fertilizer nitrogen input and loss[20]. In addition to nitrogen management, water-saving irrigation such as AWD (Alternative wetting and dry) irrigation, intermittent irrigation and controlled irrigation are considered as promising options to reduce nitrogen loss. Agricultural systems that improve nitrogen and water management can work together to increase grain yield, nitrogen use efficiency and water productivity, and reduce nitrogen loss[21]. At the same time, it should be noted that the spatial variability of soil is large, and the distribution of nitrogen in soil, water and gas is affected by many factors, so it is difficult to evaluate the soil nitrogen balance. As mentioned above, in recent years, biochar, as a new material, has been widely tested in all kinds of soil. Most studies have shown that biochar can effectively improve soil fertility, reduce nitrogen loss and improve nitrogen use efficiency through its own physical adsorption of exogenous nitrogen, changes in soil carbon and nitrogen cycle and related microbial activities. For example, Liu[22] found that biochar could reduce soil nitrogen surplus by 79.05%-106.33% under conventional fertilization in the North China Plain, and the application of biochar also reduced annual nitrogen loss. The citation authors believed that the minimum nitrogen loss was 88.0 kg N/hm^2 and the nitrogen surplus was 59.5 kg N/hm^2 when the biochar was applied at 13.5 t/hm2, which was the closest to the theoretical recommended value of soil nitrogen surplus in the wheat-maize rotation system in the North China Plain.

4 Conclusions

First, NO- 3 generated by soil nitrification is the substrate for the formation of N_2O, so soil nitrification directly affects the yield of N_2O. In this study, only AOB and AOA of traditional two-step nitrification were analyzed. However, in 2015, Daims and Van Kessel newly discovered whole-process ammoxidation bacteria can independently complete the nitrification process of ammonia nitrogen oxidation to nitrate in one step, which greatly expanded people's understanding of nitrification [23]. There are few studies on the influence of biochar on whole-process ammoxidation bacteria. Therefore, in the future, relevant researchers should study the effects of long-term application of biochar on the community characteristics of soil AOB, AOA and whole-process ammonia-oxidizing bacteria, as well as their relative contribution to N_2O emission. This result will provide a new idea for the effective use and management of nitrogen, and will certainly trigger a series of in-depth thinking and further research in the academic circle. Second, the soil aggregates are a key entry point for studying the mechanism of soil carbon and nitrogen cycling. As ecological niche, their unique physical and chemical properties are conducive to the heterogeneous distribution of microorganisms between different grain sizes, affecting their biochemical functions and thus affecting soil N_2O emission. However, there are few studies on this topic. Physical grouping technology is used to separate different functional components. On this basis, combining with molecular biotechnology technologies such as real-time PCR and DGGE, the interaction mechanism between the abundance and community diversity of ammonia oxidizing bacteria and denitrifying bacteria and N_2O emission in different functional components is analyzed, which is helpful to reveal the biochemical function of biocharcoal. It is important to understand the mechanism of biochar affecting soil nitrogen cycling and greenhouse gas emissions. Third, the types of biochar are diverse, with great differences in texture, specific surface area, porosity, pH, nutrients contained and adsorption properties. So the results of many studies are not very comparable. Now it is urgent to formulate a set of biochar production standards to specify the raw materials, production process and effects of biochar production, so as to produce biochar adapted to different types of soil in this set of standards. Fourth, greenhouse gases or other pollutants generated during the production and transportation of biochar should also be considered in future studies.

Acknowledgment

This study was supported by the Technical Standard Construction Project of Ecological paddy Field Construction in the Yellow River Basin (SDMLZY2203-01) and the Innovation Project of Shandong Academy of Agricultural Sciences.

References

1. Tarin M W K, Khaliq M A, Fan L, et al. Divergent consequences of different biochar amendments on carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from the red soil[J]. Science of The Total Environment, 2020, 754:141935.
2. Liu H, Li H, Zhang A, et al. Inhibited effect of biochar application on N_2O emissions is amount and time-dependent by regulating denitrification in a wheat-maize rotation system in North China[J]. Science of The Total Environment, 2020, 721:137636.
3. Yanai Y, Toyota K, Okazaki M.Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments[J]. Soil Science and Plant Nutrition. 2007, 53, 181- 188.
4. Laird D, Fleming P, Wang B Q, et al. Biochar impact on nutrient leaching from a Midwestern agricultural soil[J]. Geo-derma, 2010, 158: 436-442.
5. Shi Y, Liu X, Zhang Q, et al. Contrasting effects of biochar and organic fertilizer-amendment on community compositions of nitrifiers and denitrifiers in a wheat-maize rotation system[J]. Applied Soil Ecology, 2022, 171:104320.
6. Sun L, Sang C, Wang C, et al. N_2O production in the organic and mineral horizons of soil had different responses to increasing temperature[J]. Journal of soil & sediments, 2019, 19(10):3499-3511.
7. Wang Z, Lei C, Sun F, et al. Effects of adding biochar on properties and nitrogen bioavailability of an acidic soil in Eastern China[J]. European Journal of Soil Science, 2017, 68(4):559-572.
8. Sharma D L, Anderson W K. Success of diagnostic approach to rainfed, wheat-based cropping systems in Western Australia[J]. Agricultural Systems, 2014, 123: 22-33.
9. Zhou Z M, Takaya N, Sakairi M A C, et al. Oxygen requirement for denitrification by the fungus Fusarium oxysporum[J]. Archives of Microbiology, 2001, 175(1): 19-25.
10. Cabello P, Roldán M D, Moreno-Vivián C. Nitrate reduction and the nitrogen cycle in archaea[J]. Microbiology, 2004, 150(11): 3527-3546.
11. Pina-Ochoa E, Hogslund S, Geslin E, et al. Widespread occurrence of nitrate storage and denitrification among Foraminifera and Gromiida[J]. Proceedings of the National Academy of Sciences of the United States of America, 2010, 107(3): 1148-1153.
12. Xu Y P, Xie Z B. The effect of biochar oldification on N_2O emission on paddy soil and red soil[C]. In:Biochar Research Development and Application, Nanjing, 2011: 54.
13. MU Islam, Jiang F, Guo Z , et al. Does biochar application improve soil aggregation? A meta-analysis[J]. Soil and Tillage Research, 2021, 209:104926.
14. Zhang M, Cheng G, Feng H, et al. Effects of straw and biochar amendments on aggregate stability, soil organic carbon, and enzyme activities in the Loess Plateau, China[J]. Environmental Science & Pollution Research, 2017, 24(11):1- 13.
15. Drury C F, Yang X M, Reynolds W D, et al. Influence of crop rotation and aggregate size on carbon dioxide production and denitrification[J]. Soil & Tillage Research, 2004, 79(1):87- 100.
16. Kong A Y Y, Hristova K, Scow K M, et al. Impacts of different N management regimes on nitrifier and denitrifier communities and N cycling in soil microenvironments[J]. Soil Biology & Biochemistry, 2010, 42(9):1523- 1533.

17. Ju X T, Xing G X, Chen X P, et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems[J]. Proceedings of the National Academy of Sciences of the United States of America, 2018, 106(9):3041-3046.
18. Ju X T. The concept and significance of efficiency of nitrogen fertilizer also the misunderstanding of traditional efficiency of nitrogen fertilizer[J]. Acta Pedologica sinica, 2014, 51(5):13.
19. Zhang C, Ju X T, Powlson D, et al. Nitrogen surplus benchmarks for controlling n pollution in the main cropping systems of china[J]. Environmental ence & Technology, 2019, 53(12): 6678-6687.
20. Xue L H, Yu Y L, Yang L Z. Maintaining yields and reducing nitrogen loss in rice–wheat rotation system in taihu lake region with proper fertilizer management[J]. Environmental Research Letters, 2014, 9(11): 115010.
21. Jiao J G, Shi K, Li P, et al. Assessing of an irrigation and fertilization practice for improving rice production in the Taihu Lake region (China)[J]. Agric. Water Manage, 2018, 201, 91-98.
22. Liu H Y. Effect of biochar on soil N_2O emissions in farmland of north china plain and its mechanism[D]. Chinese Academy of Agricultural Sciences, Beijing, 2020.
23. Daims H, Lebedeva E V, Pjevac P, et al. Complete nitrification by nitrospira bacteria[J]. Nature, 528(7583): 504-509.