Microbial-Mediated Emissions of Greenhouse Gas from Farmland Soils

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The greenhouse effect is one of the concerning environmental problems. Farmland soil is an important source of greenhouse gases (GHG), which is characterized by the wide range of ways to produce GHG, multiple influencing factors and complex regulatory measures. Therefore, reducing GHG emissions from farmland soil is a hot topic for relevant researchers.

Keywords: microorganism ; farmland soil ; greenhouse gas emission

1. Introduction

Greenhouse gases (GHGs) usually refer to gases that can absorb the Earth's thermal radiation and enhance the greenhouse effect, mainly, carbon dioxide (CO_2) and methane; the greenhouse effect is one of the important environmental problems humans have so far faced in the 21st century. CO_2 is the single most important anthropogenic GHG in the atmosphere, contributing approximately 66% of the radiative forcing by long-lived greenhouse gases (WMO, 2019). Soil is the largest carbon reservoir in the terrestrial ecosystem [1]; the global carbon storage in 1~3 m of soil is about 1500~2344 Gt C (1 Gt = 10^{15} g), which is about three times that of the global vegetation and two times that of the atmosphere (IPCC, 2013b). However, the respiration of microorganisms, animals and roots, and the oxidation of carbonaceous matter also produce CO_2 [2]. Not only does soil produce CO_2, but the consumption of diesel, gasoline and electricity in farmland practices such as farming, irrigation and harvesting also cause CO_2 emissions [3]. The annual global emission of CH_4 was about 580 million in 2021. CH_4 is the second most important GHG after CO_2, with an average lifetime of about 8.75 years in the atmosphere and a contribution rate of about 15% of the greenhouse effect. The warming effect of CH_4 per unit mass in 20 years is about 84~87 times that of CO_2, and its warming effect in 100 years is about 28~36 times that of CO_2 [4]. The main emission sources of CH_4 in agriculture are rice and livestock cultivation, and the anaerobic environment of flooded rice fields and animal intestine create favorable conditions for CH_4 production by methanogens. The main sources of CH_4 are natural wetlands, human activities and biomass burning, and tropical regions with high CH_4 emissions contribute 80% of global CH_4 emissions [5]. N_2O is another noteworthy GHG, accounting for about 7.9% of the greenhouse effect. Its average lifetime in the atmosphere is 114 years, and its global warming potential (GWP) is 296~310 times that of CO_2, which is the main destroyer of stratospheric ozone [6]. Nitrogen fertilizer application in agriculture is the main source of N_2O, and N_2O emissions caused by fertilization account for about 30% of global land emissions. Therefore, reducing N_2O emissions from farmland soil is urgent to alleviate the greenhouse effect [7][8][9].

2. Biochar

Biochar is a loose and porous substance with a high carbon content produced by carbonization organic materials under the condition of little or no oxygen. It has the characteristics of wide source, low cost, large specific surface area, strong adsorption capacity and strong carbon stability. Biochar can improve soil fertility and increase crop yield in agricultural applications. It has reportedly shown great potential in reducing GHG emissions in soils. A large number of experiments have found that fresh biochar cannot reduce CO_2 emission in soil [10][11][12][13], while biochar has been naturally aged in field soil, and the organic and inorganic complexes that accumulate on the surface of soil minerals can stabilize the organic carbon in biochar, structurally increasing spatial resistance and reducing CO_2 emissions from a physicochemical perspective [14]. In addition, compared with fresh biochar, aged biochar has a richer microbial community structure [15], and some CO_2-fixing bacteria appear, which reduces CO_2 emission on the microbial level [16].

The reduction in CH_4 emission by biochar is due to the joint action of physical chemistry and microorganisms in the soil. The application of biochar increases soil aeration and redox potential, which results in the reduction in CH_4 emission by physical–chemical reaction. Methanogens are obligate anaerobic bacteria, which are the main microorganisms producing

CH_4 in the soil. After entering the soil, biochar with high porosity inhibits the activity of most methanogens and affects the change of microbial community in the soil [17]. Wang et al. monitored the microbial community after biochar application in soil for four consecutive years; the experimental results showed that the abundance of methanogens in the soil after long-term biochar application significantly decreased, while the abundance of methane-oxidizing bacteria did not change significantly, thus, reducing the emission of CH_4 in paddy fields [18].

The short-term addition of biochar to rice soil increased the abundance of ammonia-oxidizing bacteria (AOB) and ammonia monooxygenase gene (*amoA*), and significantly increased the denitrification rate of the soil. Fresh biochar provided a stronger alkaline environment and nutrients, and even improved the denitrification capacity and nitrogen emission [19]. Many studies have shown that fungi make a greater contribution to N_2O production than bacteria in acid soil [20][21]. As the denitrification product of fungi is N_2O instead of N_2, reducing the number of fungi in soil can reduce N_2O emissions. Adding biochar and nitrogen fertilizer to acid soil with high N_2O emission will increase the soil pH, change the community composition of fungi, inhibit the denitrification of fungi, significantly reduce the abundance of fungi, increase the abundance of the *nosZ* gene, enhance the activity of N_2O reductase, and promote bacteria to reduce N_2O to N_2 [22]. *nosZ I* and *nosZ II* are N_2O reductase coding genes widely existing in the environment. Studies have shown that microbes containing the *nosZ II* gene have greater N_2O reduction potential. Some microbes containing the *nosZ II* gene lack the nitrite reductase gene, so they do not produce N_2O during denitrification, which provides a new research idea for N_2O emission reduction in the future.

Although biochar can improve carbon sequestration, achieve emission reduction and adjust the abundance and activity of microorganisms related to GHG emissions in soil, it also has the health risk of releasing heavy metals, organic pollutants, nanoparticles and other substances to inhibit the growth and development of crops. Nanoparticles extracted from six biochars by Zhang et al. were confirmed to inhibit the germination of rice seeds and the growth of reed roots [23]. After biochar enters the soil, soil alkalinity will be enhanced, which will reduce the utilization rate of trace elements such as Fe, Zn and Cu in the soil, interfere with crop growth and even cause plant death [24]. Some studies have found that pollutants in biochar cause serious harm to earthworms [25], and excessive biochar directly reduces their survival rate [26]. Therefore, the application of biochar needs to be considered in combination with the actual soil environment, nature and other factors.

3. Organic Fertilizer

Organic fertilizer is the best substitute for chemical fertilizer by using agricultural, animal husbandry and industrial wastes as raw materials to turn waste into treasure. Organic fertilizer can significantly improve soil quality, enrich the microbial community and increase crop yield. However, studies have shown that the introduction of organic fertilizer into the soil will increase the content of light component organic carbon, which is more easily used by microorganisms, and the application of organic fertilizer alone will significantly increase soil CO_2 emission [27]. Wang et al. and Li et al. adopted the mode of fertilizer reduction combined with organic fertilizer application and found that soil carbon sequestration significantly increased and GHG emissions significantly decreased in double-cropping rice fields [28][29]. Studies have shown that CH_4 effluxes were significantly and negatively related to *mcrA* and *pmoA* gene copy numbers, and positively related to *mcrA*/*pmoA*. Organic fertilizers provide substrates for methanogens and promote the production and emission of CH_4 [30][31]. Li et al. replaced a part of inorganic fertilizer with organic fertilizer in the soil, and five substitution rates including 0, 20%, 50%, 80%, and 100% and a no fertilizer control were evaluated on Chinese cabbage. Cylindrical PVC chambers were placed at the center of each plot on each sampling day at 9 a.m. to collect gas. They found that organic fertilizer could reduce the emission of N_2O, and the quality of the vegetables improved under the substitution rate of 20~50% [32]. In summary, the rational use of organic fertilizer can not only regulate C/N in the soil, thereby changing the dominant species of microorganisms in the soil, but also increase crop yield and alleviate the GHG effect. Therefore, significant experimentation and research are needed to find the best case.

4. Straw Returning

Straw returning is a comprehensive utilization measure widely adopted around the world, which has the advantages of fertilizing soil capacity, improving cultivated land quality, and increasing soil carbon reservoir and crop yield. As an agricultural renewable resource, straw contains N, P, K, Ca, Mg and other mineral elements needed for crop growth. The main components of straw are abundant organic carbon such as cellulose, hemicellulose and lignin, which can improve the soil organic matter content after returning to the field. There are differences in the composition of straw from different crops, which have different effects on GHG emissions in the soil after returning to the field. Zuo et al. studied the effect of returning corn straw pretreated with white rot fungi on soil GHG emissions, and the results showed that the emissions of CO_2 and N_2O increased significantly due to the increase in C and N content [33]. Recent studies have also suggested that straw return significantly increased the net GWP compared to non-straw return [34], which is consistent with the results of Wu et al., who reported that straw return increased GHG. Research on straw returning significantly increasing CH_4 emissions has been widely reported [35]. Wang et al. found that straw returning significantly increased CH_4 emissions by using the method of meta-analysis, and the comprehensive temperature potential of GHG significantly increased by 87.1% [36]. The impact of straw returning on N_2O is still uncertain. Li et al. and Liu et al. believed that straw returning increased the content of C in the soil, enhanced the denitrification of microorganisms in the soil, and promoted the emission of N_2O [37][38]. Xu et al. studied the impact of nitrogen fertilizer and straw on N_2O emission from winter wheat farmland. Four treatments, i.e., no N fertilizer and no straw, straw incorporation only, N fertilizer only, and N fertilization plus straw incorporation, were established in the experiment. They found that straw incorporation increased the N content in the soil but had no significant impact on N_2O emission [39]. Chen et al. used ^{15}N tracing technology to study the mechanism of N_2O increase after straw return [40]. They found that the C/N ratio of straw application was negatively related to soil denitrification, and increasing the C/N ratio of straw application could weaken the N_2O emission during denitrification. Straw returning significantly affects the soil microbial community structure, and the dominant bacteria in the straw degradation process will also change over time. In order to reduce GHG emissions, the strategy of straw incorporation should be adjusted. There is a research gap in the impact of straw return on GHG, which still needs to be studied by relevant professionals.

5. Microalgae Biofertilizer

Microalgae are widely distributed unicellular or simple multicellular microorganisms in land, lake and sea. Microalgae can efficiently carry out photosynthesis and be used for energy production, wastewater treatment and CO_2 reduction. Microalgae biofertilizer is mainly composed of eukaryotic green algae with high photosynthetic efficiency and prokaryotic cyanobacteria with fixed nitrogen. Microalgae biofertilizer is rich in trace elements and has the advantages of high efficiency, environmental protection, carbon fixation and nitrogen fixation to reduce GHG emissions [41]. The photosynthetic efficiency of microalgae is 10~50 times that of ordinary terrestrial plants. Microalgae can fix CO_2 from the atmosphere and increase O_2 content in the soil by absorbing CO_2 in the environment and releasing O_2 at the same time [42]. Microalgae in the soil can activate solidified phosphorus and potassium in soil under the action of biological enzymes, improve the activity of cationic mineral elements in soil, and promote the accumulation and transformation of photosynthetic products. The extracellular polysaccharides secreted by microorganisms and microalgae on the soil surface will form a layer of algal biofilm, which can increase the carbon and nitrogen sources in the soil by sequestering CO_2 and N_2 in the atmosphere [43]. Marks et al. added the suspension of chlorella culture to farmland soil, accelerating the formation of soil photosynthetic biofilm [44].

Cyanobacteria have both carbon and nitrogen-fixation functions. CO_2 in the atmosphere is fixed through photosynthesis, similar to green algae. The cyanobacteria are divided into vegetative and highly differentiated heterocyst cells. Heteroplasts have a unique nitrogenase, which can reduce N_2 to NH_3. Nitrate reductase and nitrite reductase in vegetative cells convert nitrate and nitrite in the environment to NH_3 through nitrification and denitrification, increasing soil nitrogen reserves [45]. Nitrogen-containing substances such as amino acids, sugars, polysaccharides and a small number of hormones secreted by cyanobacteria during their growth and reproduction further increase the content of effective nitrogen in the soil [46][47]. Ali et al. showed that the CH_4 emission flux of Bangladeshi rice soil treated with azolla and cyanobacteria was low in two consecutive rice experiments, 12% lower than that of the control [48]. Prasanna et al. conducted experiments in paddy fields in New Delhi, India, and found that the CH_4 emission of rice soil inoculated with two kinds of Anabaena biofilm (Anabaena—Trichoderma, and Anabaena—*Pseudomonas aeruginosa*) was 50~80% lower than that of rice fields under the traditional mode [49]. Shrestha et al. found that, compared with urea, microalgae biofertilizer did not significantly increase wheat yield, but reduced nitrogen oxide (N_2O and NO) emissions in soil [50]. Zhang et al. and Hu et al. tried to combine microalgae biofertilizer with biochar or organic fertilizer and found that the carbon sequestration ability of microalgae was significantly improved [51][52]. The reason for this is that the addition of biochar and organic fertilizer increases the intracellular glucose content of microalgae, and microorganisms are more likely to obtain extracellular glucose; thus, a large amount of intracellular glucose becomes a part of soil carbon sink, strengthening the carbon sequestration ability of microalgae. It has been reported that microalgal biofertilizer can not only sequester carbon, fix nitrogen and reduce GHG emissions, but the dead algal cells can be converted into organic matter and improve soil fertility and plant yield [53]. Microalgae carbon fixation is also widely used in the treatment of coal-fired flue gas in factories. Microalgae fix CO_2 in coal-fired flue gas through photosynthesis, and absorb NO_x and SO_x in flue gas as nitrogen and sulfur sources for their own growth and reproduction [54][55]. Microalgae, the product of industrial carbon fixation, happens to be an important source of microalgae biofertilizer, which will become an effective medium for industrial and agricultural carbon emissions reduction. Under the background of global green production, microalgae have broad application prospects and are important resources for future development.

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