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# Microbial-Mediated Emissions of Greenhouse Gas from Farmland Soils: A Review

**Han Wang [1], Rui Zhao [1], Dan Zhao [1], Shejiang Liu [1], Jianfeng Fu [1], Yuxin Zhang [2], Nan Dai [2], Dan Song [3] and Hui Ding [1,*]**

[1] School of Environment Science and Engineering, Tianjin University, Tianjin 300072, China
[2] College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China
[3] Chongqing Academy of Eco-Environmental Sciences, Chongqing 401147, China
* Correspondence: dinghui@tju.edu.cn

**Abstract:** 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. This review systematically expounds on the main pathways of soil $CO_2$, $CH_4$ and $N_2O$; analyzes the effects of soil temperature, moisture, organic matter and pH on various GHG emissions from soil; and focuses on the microbial mechanisms of soil GHG emissions under soil remediation modes, such as biochar addition, organic fertilizer addition, straw return and microalgal biofertilizer application. Finally, the problems and environmental benefits of various soil remediation modes are discussed. This paper points out the important role of microalgae biofertilizer in the GHG emissions reduction in farmland soil, which provides theoretical support for realizing the goal of "carbon peaking and carbon neutrality" in agriculture.

**Keywords:** microorganism; farmland soil; greenhouse gas emission; microalgae biofertilizer

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## 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 [7–9].

At present, researchers have developed some measures and technologies for GHG emission reduction in farmland soil, mainly including adding biochar, returning straw to the field, and applying organic fertilizer or microalgae biofertilizer and soil improvers (such as lime and nitrification inhibitor, etc.) [10–14]. Microbes play a crucial role in the application of these mitigation measures and technologies. However, there are few reviews on the role of microorganisms in GHG emissions from farmland. This review summarizes the sources of $CO_2$, $CH_4$ and $N_2O$ in farmland soils, and discusses the environmental impact factors of microorganisms in farmland soil GHG emissions and the GHG emission reduction mechanisms of microorganisms under different soil remediation modes.

## 2. GHG Production in Agroecosystem

The agroecosystem is an important source of $CO_2$. Agricultural processes generate 15 billion tons of $CO_2$ emission, accounting for 30% of global total emissions [15]. $CO_2$ emission from the soil is usually called "soil respiration", which is a process of metabolism of animals, roots, fungi and bacteria in the soil. It involves three biological processes (plant root respiration, soil microbial respiration and soil animal respiration) and one non-biological process (chemical oxidation of carbon-containing substances) [2,16]. $CO_2$ in the atmosphere converts into organic matter through the photosynthesis of plants, and then the carbon in the organic matter enters the soil in the form of root exudates, dead roots or fallen leaves. Under the action of soil microorganisms, it is transformed into soil organic matter and stored in the soil, forming soil carbon sink.

The agroecosystem is an important source of $CH_4$ emissions, accounting for 15~30% of the total emissions [17]. In soil with poor aeration, low carbon organic acids, $H_2$, $CO_2$ and other substances formed by the fermentation of other microorganisms generate $CH_4$ under the action of methanogens. $CH_4$ in the agroecosystem can be generated in two ways: (1) organic acids in the soil environment or the degradation products of organic acids, $CO_2$ and $H_2$ generate $CH_4$ under the action of methanogens, or methanogens use formic acid and CO to form $CH_4$; (2) the demethylation of methyl compounds under the action of methanogens to produce $CH_4$. Methane-oxidizing bacteria account for the largest proportion in dryland soil with good aeration. About 82% of $CH_4$ is absorbed and utilized by methane-oxidizing bacteria in the soil before being discharged into the atmosphere, and then entering the soil ecosystem [18,19].

$N_2O$ discharged from farmland soil is mainly a by-product of microbial nitrification and denitrification, in which nitrification is divided into autotrophic nitrification and heterotrophic nitrification, and autotrophic nitrification is divided into two stages: (1) ammonia oxidation stage: ammonia-oxidizing archaea (AOA) and bacteria (AOB) first oxidize $NH_3$ to $NH_2OH$ and then reduce it to $NO_2^-$; (2) nitrite oxidation stage: $NO_2^-$ is oxidized to $NO_3^-$ by nitrite-oxidizing bacteria. Heterotrophic nitrification is the transformation of organic ammonia nitrogen into $NO_2^-$ and $NO_3^-$ by nitrifying bacteria and fungi in an aerobic environment [20]. Denitrification is a process in which microorganisms reduce $NO_3^-$ and $NO_2^-$ to NO, $N_2O$ and $N_2$ in the presence of anaerobic environment and various enzymes [21]. When the atmospheric pressure and soil moisture content change, $N_2O$ in the atmosphere will enter the soil pores through physical diffusion, and the water and solution in the soil will also dissolve $N_2O$ in the atmosphere, thus, introducing $N_2O$ into the agroecosystem [22]. The production process of $CO_2$, $CH_4$ and $N_2O$ in farmland soil is shown in Figure 1.

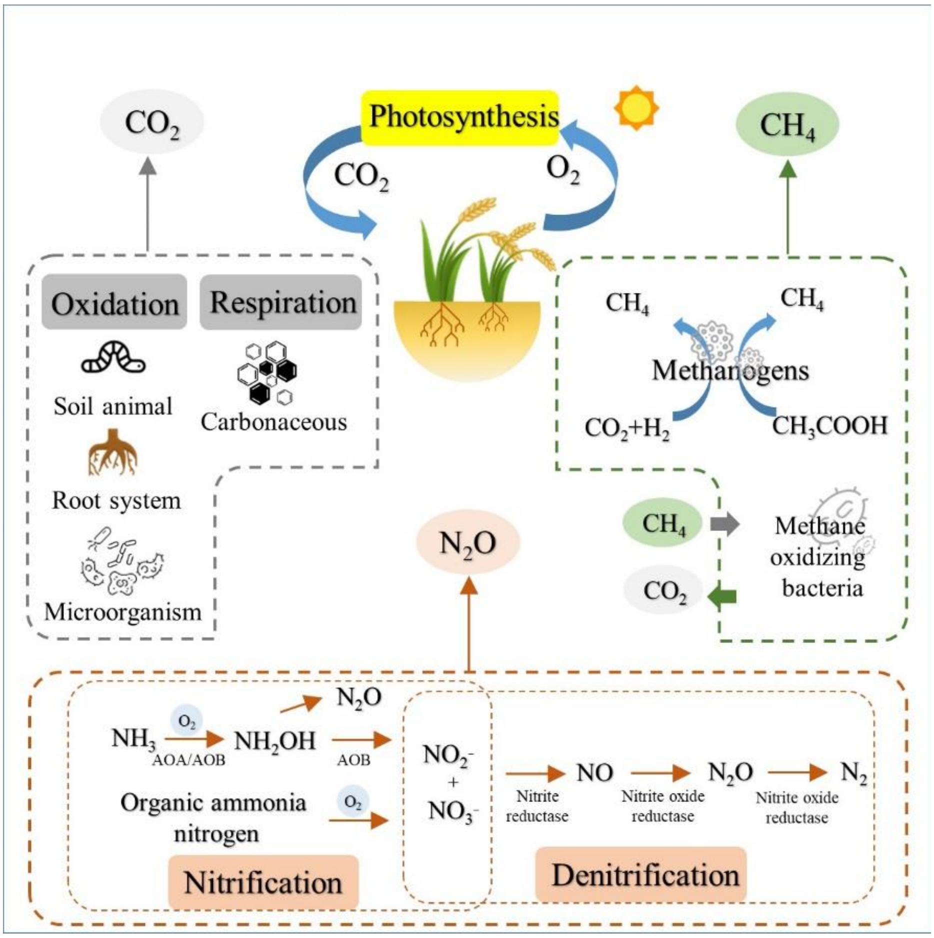


**Figure 1.** The production process of $CO_2$, $CH_4$ and $N_2O$ in farmland soil.

## 3. Environmental Factors Affecting GHG Emissions of Microorganisms in Farmland Soil

### *3.1. Soil Temperature*

A large number of studies have shown that temperature is the main factor affecting the production and emissions of GHG in soil [23–25]. Higher soil temperature can enhance the root respiration of crops, accelerate the decomposition of organic matter in the soil, improve the activity of microorganisms in the soil, and thus, accelerate the diffusion of $CO_2$ in soil [26,27]. Methanogens and methane-oxidizing bacteria jointly determine the emission of $CH_4$. Within a certain temperature, the metabolic capacity of methanogens is positively correlated with temperature. When the ambient temperature rises from 20 °C to 35 °C, the emission of $CH_4$ will double. However, recent studies have proposed that methanogens have thermal adaptability, and microbial activity decreases after long-term warming and increases after long-term cooling [28]. Walker et al. explored the response mechanism of soil microorganisms to temperature changes through in situ natural warming experiments, and the results showed that microbial temperature sensitivity and substrate consumption jointly affected soil carbon loss by controlling microbial biomass [29]. In the experiment of soil transplantation on a 3000 m elevation gradient in a tropical forest, every 1 °C increase in temperature resulted in a 4% decrease in soil carbon content. In addition to the decomposition of soil organic matter directly caused by temperature rise, temperature rise affected the physiological function of microorganisms, such as carbon utilization efficiency, microbial community change and the positive feedback effect of related enzyme activity [30]. The production of $N_2O$ in soil has biological and abiotic pathways, and high temperature will stimulate microbial activity. Cui et al. conducted a liquid culture of *Pseudomonas mandelii* at 10~30 °C and found that its denitrification activity is proportional to the temperature [31]. Studies have found that high temperature has a more significant effect on the production of $N_2O$ by abiotic pathways, and abiotic denitrification at 50 °C has the strongest effect and the highest $N_2O$ emission [32].

### 3.2. Soil Moisture

Soil moisture affects the emissions of GHG from soils by changing the microbial activity and soil porosity in the soil itself. Soil $CO_2$ emission shows a Birch effect with soil moisture: a certain water content stimulates microbial activity and increases $CO_2$ emission, while too high a water content inhibits soil respiration [33]. Zou et al. studied GHG emissions patterns under different hydrological conditions and found that $CO_2$ equivalent emissions were the lowest when the groundwater level was close to the surface [30]. The utilization rate of $O_2$, the activity of microorganisms and the diffusion ability of gas molecules in soil are all affected by soil water content. Soil with a high water content is prone to form anaerobic areas, which promote the growth of methanogens and denitrification, thus, resulting in an increased emission of $CH_4$ and $N_2O$ in soil [34,35]. The Paddy field is the main place where $CH_4$ and $N_2O$ are produced, and its irrigation mode significantly affects the GHG emissions of the soil. Intermittent irrigation will inhibit the activity of methanogenic bacteria and reduce $CH_4$ emissions. Flooding irrigation provides an anaerobic environment to promote denitrification, but excessive water delays the diffusion of $N_2O$, resulting in the reduction of $N_2O$ to $N_2$ and $N_2O$ emission being reduced [36]. According to the above, the International Paddy Field Research Institute put forward the water management mode of dry–wet alternation; the lower redox potential of flooded soil is beneficial to the production of $CH_4$, and the higher redox potential of drained soil is beneficial to the production of $N_2O$ [37]. By controlling the time of wet–dry alternation, the redox potential of soil is maintained at a moderately low level, and the lowest emissions of GHG is achieved [38]. Liao et al. found that soil moisture and atmospheric temperature will affect $N_2O$ emission by adjusting the balance between nitrifying bacteria and denitrifying bacteria [36]. Soil moisture decreases with the increase in atmospheric temperature, which increases the gene abundance of *amoA* encoding nitrification to produce $N_2O$ in soil, and the decrease in gene abundance of *nosZ* (Recombinant Nitrous-oxide reductase) encoding $N_2O$ reduction to $N_2$, thus, increasing $N_2O$ emission [39].

### 3.3. Soil Organic Matter

Soil organic matter (SOM) generally refers to a type of polymer organic compound with complex components and stable properties formed by organic residues in the soil through microorganisms or other physical and chemical processes [40]. SOM is a major carbon source for soil respiration and significantly affects soil GHG. Soil-activated organic C is a substrate for microbial growth, and its content directly affects the activity of microorganisms, which in turn affects the emission of GHG. Soluble organic matter content in SOM is closely related to $CO_2$ production in soil [41,42], and Paré and Bedard et al. found that alkane carbon and aromatic substances in the arctic tundra ecosystem enhanced $CO_2$ emission [43]. Wang et al. and Pascual et al. found that amines and aromatic compounds in the soil increased significantly after straw returned, resulting in higher $CO_2$ emissions [44,45]. SOM is the main substrate of methanogens, and the SOM content is positively correlated with the $CH_4$ emission [46]. Most denitrifying bacteria are chemoheterotrophic, and their energy for production and reproduction mainly comes from soil organic matter. Therefore, a high organic matter content provides sufficient energy for denitrification and promotes the production of $N_2O$ [47]. Other studies have found that microorganisms decompose organic matter and consume oxygen, inhibit soil nitrification and reduce $N_2O$ emission [48]. That this is due to the C/N in the soil directly affects the decomposition of SOM and the activity of microorganisms, thereby inhibiting or promoting the emission of $N_2O$ from the soil [49].

### 3.4. Soil pH

The activities of microorganisms and enzymes in soil, the decomposition of organic matter and the development of crop roots are closely related to soil pH. The influence of soil pH on $CO_2$, $CH_4$ and $N_2O$ emissions is complex. The optimum pH of most microorganisms in soil is 6–8, and too acidic or too alkaline an environment will inhibit the activity of microorganisms and reduce the emissions of GHG. The optimal pH for the growth and reproduction of methanogens is about 7 [50], and the acidic environment will reduce the emission of soil $CH_4$. $N_2O$ reductase is the only enzyme that converts $N_2O$ into $N_2$ during denitrification. Acidic soil will inhibit its activity or even cause its inactivation. Studies have found that the emission of $N_2O$ in neutral soil is significantly lower than that in acidic soil [51,52]. Therefore, adding alkaline amendments such as $CaMg(CO_3)_2$, $CaCO_3$, $Ca(OH)_2$, CaO and other lime materials in acidic soil is beneficial to improve the activity of $N_2O$ reductase and reduce the emission of $N_2O$ [53]. Shaaban et al. and Wu et al. modified acidic soil with dolomite under different water gradients, and the results showed that soil pH increased rapidly after dolomite application, which promoted the conversion of $N_2O$ into $N_2$ and reduced $N_2O$ emission [54,55]. Shaaban et al. found that the concentration of $NH_4^+$-N decreased rapidly with time, while the concentration of $NO_3^-$-N gradually increased after lime material was added to acidic soil, which indicated that nitrification in soil was strengthened [56]. The microorganisms consumed $N_2O$ as an electron acceptor instead of $NO_3^-$-N at higher $NO_3^-$-N concentrations. A large amount of $N_2O$ is converted into $N_2$ under the action of microorganisms, thereby reducing the emission of $N_2O$ [56].

## 4. Microbial-Mediated Soil Emissions Reduction Mechanism under Different Soil Remediation Modes

### 4.1. 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 [57–60], 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 [61]. In addition, compared with fresh biochar, aged biochar has a richer microbial community structure [62], and some $CO_2$-fixing bacteria appear, which reduces $CO_2$ emission on the microbial level [63].

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 [64]. 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 [65].

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 [66]. Many studies have shown that fungi make a greater contribution to $N_2O$ production than bacteria in acid soil [67,68]. 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 $N_2$ [69] (Figure 2). *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.

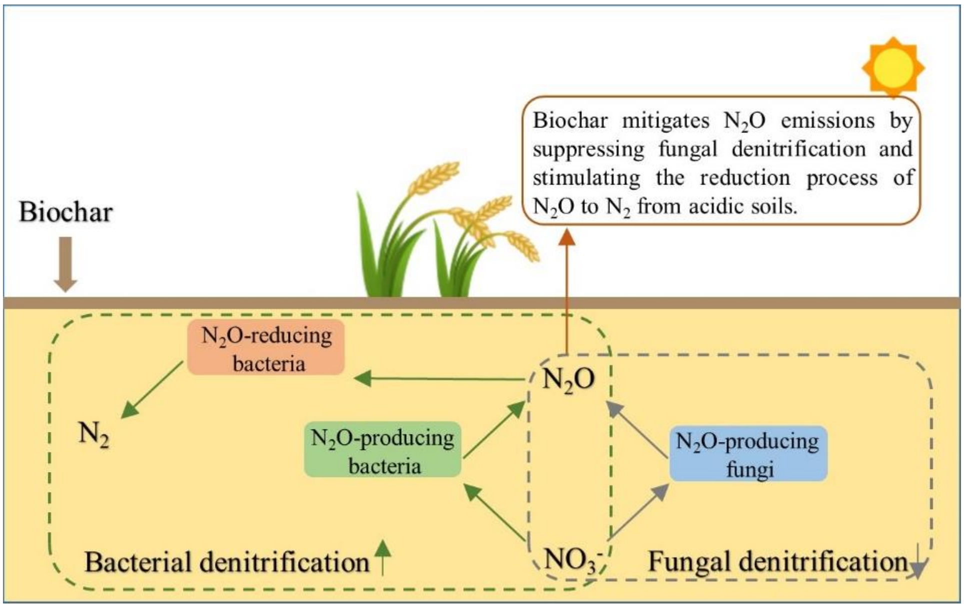


**Figure 2.** Potential mechanism of $N_2O$ emission reduction following biochar amendment from acidic soils.

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 [70]. 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 [71]. Some studies have found that pollutants in biochar cause serious harm to earthworms [72], and excessive biochar directly reduces their survival rate [73]. Therefore, the application of biochar needs to be considered in combination with the actual soil environment, nature and other factors.

### *4.2. 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 [74]. 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 [75,76]. 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 $CH_4$ [77,78]. 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% [79]. 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.

### *4.3. 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. As shown in Table 1, 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 [11]. Recent studies have also suggested that straw return significantly increased the net GWP compared to non-straw return [80], 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 [81]. 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% [82]. 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 $N_2O$ [83,84]. 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 [85]. Chen et al. used $^{15}N$ tracing technology to study the mechanism of $N_2O$ increase after straw return [86]. 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.

**Table 1.** The emission data of the GHGs from straw addition.

| Soil Type | Straw Type | GHG | Compared with No Straw Addition | Year | Ref. |
|---|---|---|---|---|---|
| Rice-wheat | Rice-wheat | $CH_4$ | +35.0% | 2015 | [87] |
| Rice-rapeseed | Rapeseed | $CO_2$<br>$CH_4$ | +6.3%<br>+32.9% | 2016 | [88] |
| Maize-crop | Maize straw | $N_2O$ | −11.0~27.0% | 2017 | [89] |
| Rice paddy | Rice straw | $CH_4$<br>$N_2O$ | +39.1%<br>−77.8% | 2017 | [48] |
| Rice paddy | Rice straw | $CO_2$<br>$CH_4$<br>$N_2O$ | +14.8~27.5%<br>+36.9~182.1%<br>−23.5~40.6% | 2019 | [90] |
| Rice-wheat | Wheat | $CH_4$ | +36.6~80.1% | 2021 | [91] |
| Rice-wheat | Rice-wheat | $CH_4$<br>$N_2O$ | +41.20%<br>+47.50% | 2021 | [80] |
| Rice-wheat | Rice-wheat | $CH_4$<br>$N_2O$ | +5.4~72.2%<br>−3.3~31.4% | 2021 | [92] |
| Wheat | Wheat | $CO_2$<br>$N_2O$ | +11.5~28.3%<br>+37.1~48.4% | 2022 | [93] |

### *4.4. 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 [94]. The beneficial effects of microalgae on soil and GHG are shown in Figure 3. 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 [95]. 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 [96]. Marks et al. added the suspension of chlorella culture to farmland soil, accelerating the formation of soil photosynthetic biofilm [97].

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 [98]. 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 [99,100]. 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 [101]. 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 [102]. 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 [103].

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 [104,105]. 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 [106]. 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 [107,108]. 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.

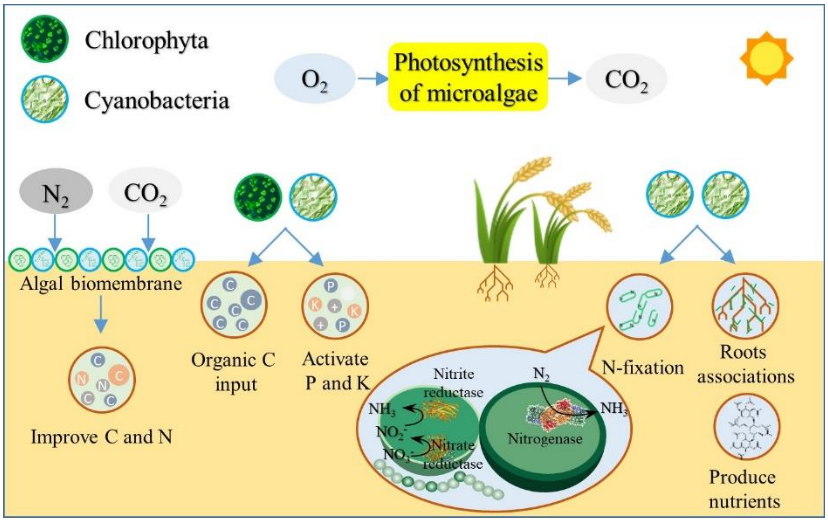


**Figure 3.** Beneficial effects of microalgae on soil and GHG emissions.

## 5. Conclusions and Prospects

There are many factors affecting GHG emissions from farmland soils. Soil temperature, soil moisture, soil organic matter content and soil pH, as well as other soil physical and chemical properties change soil GHG emissions by affecting the activities of soil microorganisms and related enzymes. At present, the feasible technologies to control soil GHG emissions include biochar application, organic fertilizer application, straw return and microalgae biofertilizer application. However, there are heavy metals, polycyclic aromatic hydrocarbons and other organic pollutants in biochar, which may inhibit crop growth, reduce crop yield and affect the growth and reproduction of soil animals after application; the organic fertilizer application and straw return require high operation and technology, so the emission reduction effect in actual application is not stable.

Here, we emphasize a remediation mode of "microalgae biofertilizer" with future development prospects. Microalgae biofertilizer satisfies people's demands for healthy soil; it achieves environmental protection, and agricultural quality and efficiency improvement through multiple functions such as carbon fixation and nitrogen fixation, crop growth promotion and soil improvement. However, there are few reports on the response mechanism of microorganisms in soil after applying microalgae biofertilizer. Therefore, it is significant to explore the underlying mechanism through the GHG emissions of soil after applying microalgae biofertilizer and the metagenome sequencing technology, which will provide important theoretical support for the development of microalgae biofertilizer.

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