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Review

The Impact of the Soil Environment and Surface Mulching on N_2O Emissions from Farmland

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Abstract: A reduction in emissions of nitrous oxide (N_2O), one of the three major greenhouse gases, is important for achieving environmental sustainability and carbon neutrality goals. Agricultural fields are the primary source of N_2O emissions, and their management measures influence greenhouse gas emission reductions and the greening of agriculture. Among these practices, cover cropping plays a key role in promoting sustainable agricultural production as a major cropping technique for efficient water use and increasing crop yields in water-scarce regions worldwide. The present paper systematically reviews the influence of various soil environmental factors, such as soil temperature, moisture, pH, carbon, and nitrogen contents, as well as nitrogen cycle-related enzymes, microorganisms and mulching practices, including general mulching and straw mulching, on N_2O emissions from agricultural fields. This review suggests that future research should explore the long-term effects of different mulching materials and their application rates and durations on soil N_2O emissions. Furthermore, a networked mathematical model for causal analysis should be employed in future research to elucidate the relationships among soil environmental factors, nitrogen cycle microorganisms, and soil N_2O production and consumption. These future studies will help to deepen our understanding of nitrogen cycling processes in agroecosystems with the aim of developing environmentally friendly agricultural technologies and promoting green and sustainable agricultural development.

Keywords: emission; soil environment; mulching; microorganisms

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1. Introduction

Nitrous oxide (N_2O), a major global greenhouse gas, contributes approximately 5% to the overall greenhouse effect and has a warming potential that is over 300 times greater than that of carbon dioxide (CO_2) [1,2]. Between 80% and 90% of the N_2O generated by agricultural activities is released into the atmosphere [3], with global emissions from farmland soils estimated to be between 1.2 and 4.2 teragrams (TG). As the global population continues to grow and agricultural production intensifies, N_2O emissions from agricultural practices are expected to further rise [4,5]. This poses a serious challenge to achieving the United Nations' Sustainable Development Goals (SDGs). Nitrification and denitrification processes in soil are the primary pathways through which N_2O is released from agricultural lands [6,7]. As shown in Figure 1, the N_2O produced by these two processes accounts for 90% of all atmospheric N_2O [8]. The nitrification process carried out by nitrifying bacteria is categorized into two stages: ammonia oxidation and nitrite oxidation [9]. The ammonia

oxidation process occurs in the presence of oxygen, where NH_4^+ is converted to NH_2OH by ammonia monooxygenase (AMO), followed by the catalysis of NH_2OH to NO_2^- through hydroxyline dehydrogenase (HAO). The microorganisms involved in this process include ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) [10]. The nitrite oxidation process serves as a subsequent step, further oxidizing NO_2^- to NO_3^-, with nitrite-oxidizing bacteria (NOB) facilitating this transformation [11]. The nitrifying process (NCD), which involves coupling the nitrification reactions, refers to a reduction in the NO_2^- or NO_3^- generated by nitrification, ultimately producing N_2O and N_2 under the influence of nitrifying bacteria [12]. The nitrification process relates to the conversion of nitrite during ammonia oxidation, leading to N_2O production through the action of nitrite reductase (Nir) and nitric oxide reductase (Nor) [13]. Under anaerobic or low-oxygen conditions, heterotrophic nitrifying bacteria can reduce nitrate and nitrite in the environment to N_2O, which is subsequently converted to N_2 with the aid of nitric oxide synthase (Nos Z). This process is referred to as heterotrophic denitrification (HD) and is typically associated with N_2O production in soil [14]. These reactions can occur simultaneously; however, they are primarily influenced by factors such as soil moisture, temperature, pH, carbon-to-nitrogen ratios, and the presence of soil microorganisms [15–18]. Various environmental factors differ in their regulatory mechanisms and their degree of influence on the nitrification and denitrification pathways of N_2O emissions from farmland soils.

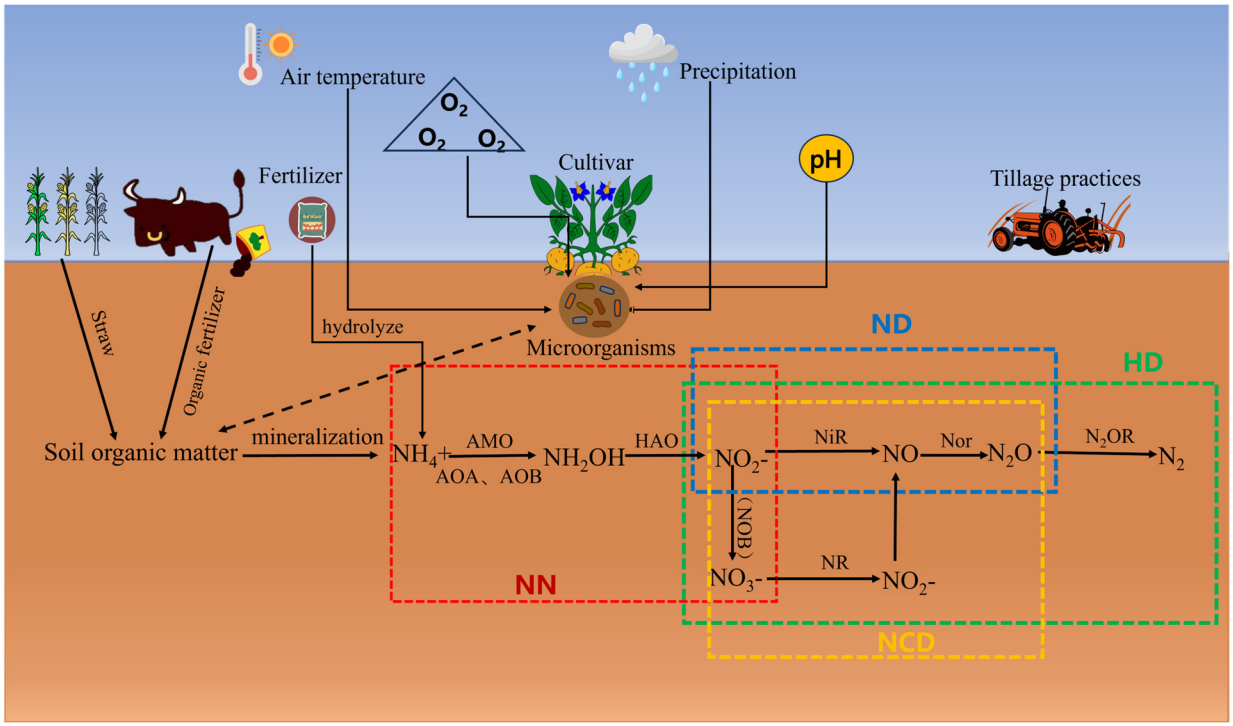


Figure 1. Process and mechanism of nitrous oxide production and emission in farmland. Note: AMO, ammonia monooxygenase; HAD, hydroxylamine dehydrogenase; NiR, nitrite reductase; Nor, NO reductase; NR, nitrate reductase; N_2OR, N_2O reductase; AOA, ammonia-oxidizing archaebacteria; AOB, ammonia-oxidizing bacteria; NOB, nitrite-oxidizing bacteria; NN, nitrification by nitrifying bacteria; ND, denitrification by nitrifying bacteria; NCD, denitrification coupled to nitrification reactions; HD, heterotrophic denitrification.

Cover cropping practices are widely adopted in agricultural production processes within drought-prone, semi-arid, and semi-humid regions due to their significant effects on enhancing crop yields [19,20]. As environmentally friendly agricultural technologies, mulching measures play an important role in improving resource use efficiency and in-

creasing the resilience of agricultural systems. Previous studies have confirmed that cover cropping can influence soil environmental factors, and these studies established that N_2O emissions from farmland are regulated by these environmental conditions. However, there is still a lack of comprehensive research examining how cover cropping alters environmental factors and subsequently affects N_2O emissions from farmland. The soil environment plays a critical role in the generation and release of N_2O, and agricultural management practices further influence these emissions by modifying soil environmental conditions. A deeper understanding of this complex relationship is important for the development of climate-smart agricultural technologies and the attainment of sustainable agriculture. The present article reviews studies on the impact of various environmental factors such as soil moisture, soil temperature, pH, soil enzymes, soil microbial communities, and the soil carbon-to-nitrogen ratio on N_2O emissions from farmland, as well as the associated research advancements and mechanisms involved. Our aim is to provide a scientific basis for optimizing mulch management practices, improving nitrogen use efficiency, and reducing greenhouse gas emissions, thereby promoting the development of agricultural systems in a more sustainable direction.

2. Environmental Factors Affecting Farmland N_2O Emissions

2.1. Soil Temperature

Soil temperature influences N_2O emissions by affecting soil nitrification and denitrification, with the extent of this influence being contingent upon both the temperature range and the soil type [21]. Under low-temperature conditions, microbial activity is inhibited, leading to reduced N_2O emissions; in fact, negative emissions may occur when temperatures approach 0 °C [22]. The optimal temperature range for nitrification is 25–35 °C, while nitrification is inhibited at temperatures below 5 °C and above 50 °C. Within the temperature range to which microorganisms are adapted, soil microbial activity exhibits a positive correlation with temperature [23]. It is widely accepted that an increase in soil temperature generally leads to an increase in N_2O emissions (Figure 2). Some studies have indicated that when the soil temperature is maintained between 15 and 30 °C, there is a positive exponential correlation between the soil temperature and N_2O emissions in soybean farmland retention paddy soil [24]. Other similar research has demonstrated that during the early and late stages of wheat growth, N_2O emission flux increases with rising soil temperatures and is significantly influenced by the air temperature [25]. However, the suitable temperature range for denitrification is between 5 and 75 °C, with the most favorable range being 30 to 67 °C. The reduction in the denitrification reaction rate at low temperatures is not pronounced; for instance, the nitrification reaction can still proceed at temperatures between 0 and 5 °C. Under a consistent soil water content and nitrate nitrogen concentration, an increase in the soil temperature from 5 °C to 10 °C results in an increase in the soil denitrification rate from 0.02 $kg{\cdot}hm^{-2}{\cdot}d^{-1}$ to 0.11 $kg{\cdot}hm^{-2}{\cdot}d^{-1}$ [26]. However, some studies suggest that lower temperatures can enhance denitrification by fungi, thereby increasing N_2O emissions [27]. This further supports the notion that the inhibitory effect of low temperatures on denitrification is not significant, with the observed differences likely attributable to other critical influencing factors. Soil N_2O emissions exhibit distinct seasonal patterns; for instance, emissions are generally higher during the humid and warm spring and summer months in the North China Plain compared to the dry and cold autumn and winter seasons [28]. Elevated temperatures accelerate the decomposition of soil organic matter, and this provides sample carbon sources for microorganisms responsible for N_2O production. This process enhances the activity of nitrification-related microorganisms, increases the reaction rate, and consequently leads to higher N_2O emissions. Additionally, rising temperatures result in increased soil respiration, which reduces the O_2 concentration

in the soil. This reduction creates anaerobic conditions conducive to denitrifying bacteria, thereby promoting the denitrification process.

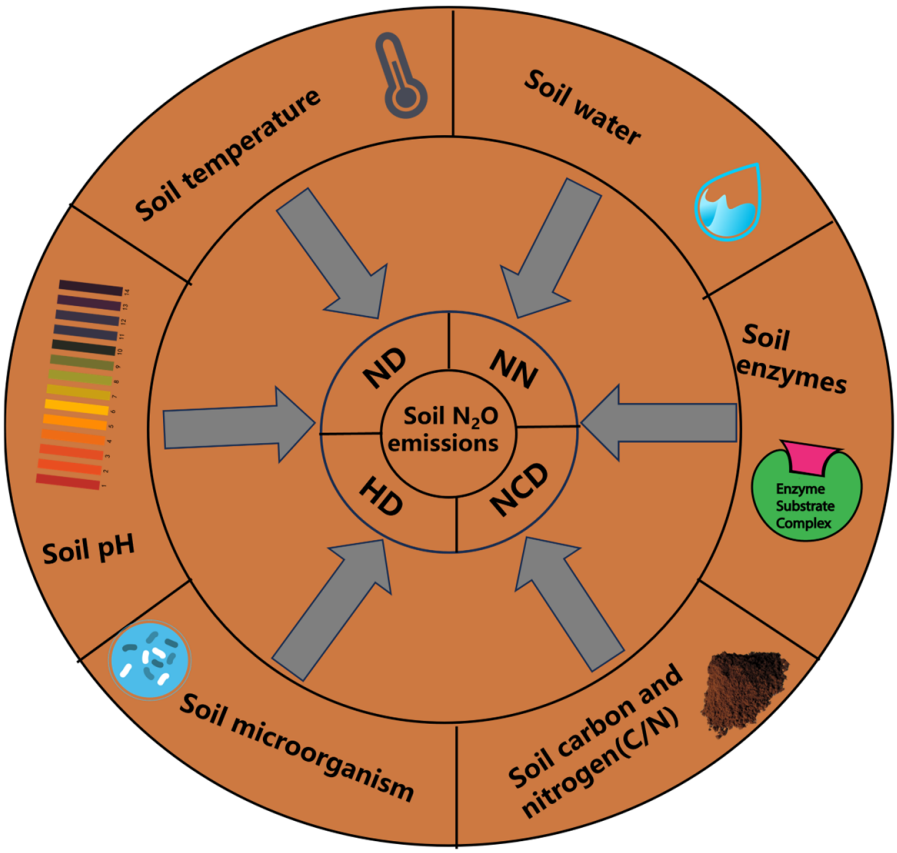


Figure 2. Effect of soil environmental factors on N_2O emissions. Note: NN, nitrification by nitrifying bacteria; ND, denitrification by nitrifying bacteria; NCD, denitrification coupled to nitrification reactions; HD, heterotrophic denitrification.

2.2. Soil Water

The soil moisture content significantly influences ventilation conditions, pore characteristics, pH values, the effectiveness of nitrogen oxidation compounds, and the activity of soil microorganisms. Furthermore, the moisture conditions of farmland are intricately linked to nutrient absorption and transfer, establishing a close relationship between farmland moisture and N_2O emissions. The soil moisture content serves as a critical factor that differentiates between nitrification and denitrification reactions. It is generally accepted that when the water content of the soil is less than 80% of the field's water-holding capacity, nitrification occurs; conversely, when the water content drops below 60%, nitrification can be considered negligible [29]. The soil pore water content, or the water filling pore space (WFPS), is a vital component of soil moisture content, characterizing the proportion of water within the total pore volume of the soil. The water content within soil pores is closely associated with soil ventilation [30]. At a WFPS of 80%, the contribution of nitrification reactions is enhanced. WFPS exhibits a negative correlation with O_2 levels, thereby serving as an indicator of O_2 content in the soil [31]. When O_2 accumulates predominantly in the surface layer of the soil, it competes with electrons for nitrogen oxides, and the high oxidation–reduction potential can hinder the growth of surface desertification. Additionally, a reduction in the accumulation of denitrification substrates can adversely affect the nitrification process, leading to decreased N_2O emissions from denitrification (Figure 2). Research indicates that when the soil WFPS ranges from 5% to 20%, N_2O emissions in cornfields can be negative, indicating the consumption of N_2O [32]. It has been found that

75–85% of the annual flux of N_2O is influenced by occasional summer rainfall events [33]. This discovery further demonstrates that the alternation between wet and dry conditions due to rainfall is often associated with peaks in N_2O emissions [34]. This phenomenon may occur because soil that is initially deficient in water becomes wet after receiving a small amount of rainfall or irrigation, leading to increased nitrification and activity of nitrifying bacteria in the soil. Consequently, the concentrations of NO_3^- and NO_2^- in the soil gradually rise, and related enzyme activity recovers. However, excessive rainfall and irrigation [35] can lead to a sharp increase in the soil moisture content, which expands anaerobic zones and enhances nitrification effects [36]. Similarly, rice experiences significant hypoxia during prolonged flooding [37], which promotes the degradation of nitrification under anaerobic conditions and further converts N_2O back to N_2, thereby reducing overall N_2O emissions [38].

2.3. Soil pH

Soil pH is a critical environmental factor that regulates soil N_2O emissions. The direct and indirect effects of soil pH influence microbial activity associated with nitrification, related enzyme activities [39], and the expression of relevant genes, all of which impact N_2O emissions [9]. The optimal pH for nitrifying reactions is 8.5, while the most suitable pH range for denitrification is between 7.0 and 8.0. When the pH exceeds 9.5, the nitrification response rate diminishes; conversely, when the pH falls below 6.0, nitrifying microorganisms are inhibited [40]. Taking AOA and AOB as examples, their responses to pH differ [41]. Under acidic conditions, AOA contribute more to N_2O during heterotrophic processes; under neutral or alkaline conditions, AOB play a more significant role in N_2O production during nitrification [42,43]. Studies indicate that at higher pH levels, the increased AOB/AOA ratio enhances potential nitrification rates, leading to elevated nitrite and N_2O emissions [44]. During nitrification, the lower soil pH diminishes N_2O reductase (N_2OR) activity while enhancing the activity of NR, NiR, and N_2OR, thereby altering the N_2O/N_2 ratio. This phenomenon occurs because H^+ ions are generated during soil denitrification, and a lower pH inhibits the positive progression of nitrification, while a higher pH promotes it through the release of OH^- ions [45]. Within a certain pH range during nitrification, the N_2OR activity increases with the rising pH under alkaline conditions (Figure 2), facilitating the conversion of N_2O to N_2 and thereby reducing cumulative N_2O emissions [46]. However, as the pH decreases, N_2OR activity is suppressed, preventing the further transformation of N_2O to N_2 and resulting in increased N_2O emissions (Figure 2). It is important to note that pH not only influences the biological channels that generate N_2O but also affects the non-biological channels related to N_2O production in the soil. Research by some Chinese scholars has demonstrated a positive correlation between NH_2OH and the non-biological conversion rate of N_2O, as well as the soil pH; specifically, as the pH increases, the rate at which NH_2OH is converted into N_2O accelerates [47].

2.4. Soil Enzymes

Soil enzymes play a crucial role in the decomposition of organic matter and the nitrogen cycle within the soil, with the magnitude of N_2O emissions being closely related to the soil enzyme activity. These enzymes are primarily derived from plant root secretions, soil microorganisms, and the remnants of dead cells [48]. The activity of soil enzymes is often employed as a metric for characterizing soil nitrogen. The enzymatic hydrolysis of urea produces ammonia and carbon dioxide, which indirectly indicates the soil's nitrogen supply capacity. Ammonia is subsequently converted to NO_2^- through nitrification, which represents the initial step in the soil nitrification process, catalyzed by AMO and HAD [49]. Under the action of nitrite-oxidizing enzymes, NO_2^- is further oxidized to

NO_3^- [50]. NO_3^- is then utilized by plants through the action of nitrifying bacteria [51]. The key enzyme in this reaction process is NR, and its activity serves as an indicator of the soil's nitrification capacity [52]. Variations in the activity of nitrifying enzymes can help distinguish N_2O emissions in dryland [50]. Studies indicate that soil N_2O emissions are significantly positively correlated with HAD activity [50]. Higher nitrogen levels correspond to increased soil urease activity, leading to lower soil N_2O flux (Figure 2) [50]. The magnitude of N_2O emissions is not influenced only by soil enzymes but also by other factors such as soil nitrogen storage, carbon sources, and growth stages [53].

2.5. Soil Microorganism

Soil microorganisms play a crucial role in soil N_2O emissions. The reduction in N_2O emissions can be achieved by altering the activity of nitrifying and denitrifying microorganisms during production. Specifically, the decrease in N_2O emissions primarily depends on the reduction in N_2O by microorganisms during the complete denitrification process. Nitrification, which is mediated by nitrifying bacteria, occurs in two stages: the first stage is catalyzed by AOB, while the second stage is facilitated by NOB [50]. Denitrification involves a diverse array of microorganisms, including over 80 genera of bacteria, as well as certain fungi, archaea, and actinomycetes [54]. In aerated soils, NOB utilize NO_2^- as the final electron acceptor, resulting in the production of N_2O [55]; conversely, nitrification does not serve as a direct source of N_2O under anaerobic conditions. Research indicates that with NOB at the microbial molecular level, the presence of N_2O-reducing bacteria containing nosZ genes significantly decreases N_2O emissions. Additionally, the application of plant rhizosphere growth-promoting bacteria with N_2O emission-reducing capabilities can alter the structure and abundance of microorganisms associated with N_2O reduction. To effectively mitigate greenhouse gas emissions [50], it is important to note that approximately 30% of denitrifying bacteria lack the nosZ gene and thus cannot reduce N_2O [56]. Furthermore, studies have demonstrated that certain strains of *Brachiaria humidicola* can secrete biological nitrification inhibitory substances, such as linoleic acid and linolenic acid, through their roots, inhibiting the activity of nitrifying microorganisms and subsequently reducing soil N_2O emissions [57]. The rate of N_2O production is closely linked to the abundance of relevant functional genes, community structure, and transcript abundance. Research has shown that the ratio of (nxrA + nxrB)/(AOA + AOB amoA) in the nitrification process increases with the elevation of the $NO_2^-/(NO_2^- + NO_3^-)$ ratio [58]. On saline–alkali land, the cultivation of leguminous crops can lead to an increase in soil N_2O emissions. Furthermore, the average N_2O emission rate exhibits a significant positive correlation with the abundance of AOB and narG-type denitrifying bacteria [59].

2.6. Soil Carbon and Nitrogen

The soil carbon-to-nitrogen (C/N) ratio significantly influences the transformation of soil nitrogen cycling, thereby regulating N_2O emissions [60]. A C/N ratio between 25 and 30 is optimal for the growth of soil microorganisms; however, when the C/N ratio exceeds 30, N_2O emissions are inhibited. In contrast, when the C/N ratio falls below 25, the microbial activity intensifies, leading to the substantial decomposition of organic matter and an increase in N_2O emissions [61]. Enhancing the proportion of effective soil carbon and nitrate nitrogen can facilitate the N_2O's reduction to N_2 [62]. Soil organic carbon serves as the primary carbon source and electron donor for heterotrophic processes. Microbial communities, driven by soil organic carbon [63], release nitrogen from soil organic matter, with some nitrogen being converted into microbial biomass. Upon the death of microorganisms, nitrogen is lost in the form of N_2O [59]. Nitrogen species, including nitrate and ammonium nitrogen, act as electron acceptors and products of microbial nitrification

and denitrification. The concentration of these nitrogen forms regulates N_2O emissions [64]. An increase in nitrate and ammonium nitrogen content can lead to elevated N_2O emissions during both nitrification and denitrification processes. Research indicates that excessive nitrogen levels may inhibit NosZ enzyme activity, consequently increasing the N_2O/N_2 ratio [65]. However, other studies have suggested that the relationship between nitrogen content and N_2O flux is not statistically significant [50].

3. The Impact of Farmland Coverage on N_2O Emissions

3.1. Plastic Film Mulching

Covering is a primary measure to combat drought and conserve moisture in water-scarce regions worldwide, which inevitably alters the soil environment and consequently affects N_2O emissions from farmland [66] (Table 1). Film covering modifies the soil environment and indirectly influences N_2O emissions [67]. Most studies suggest that film covering increases N_2O emission flux from farmland [68]. In the arid region of northwest China, the application of film coating results in higher N_2O gas emissions compared to areas without film coating [50]. A report found that mulching elevates N_2O emissions by altering the soil structure, water temperature conditions, and microbial habitats, which in turn increases both the number and activity of microorganisms and accelerates the mineralization of organic carbon and total nitrogen [69]. Furthermore, film-mulched ridge cultivation facilitates the horizontal diffusion of N_2O from the film-covered ridge surface to the non-mulched furrow surface [70]. While film mulching can mitigate the erosion and leaching of inorganic nitrogen in the soil due to rainwater, it correspondingly increases the concentrations of nitrate nitrogen and ammonium nitrogen, providing soil microorganisms with abundant substrates for nitrification and denitrification reactions, thereby enhancing N_2O emissions [71]. However, it is important to note that mulching may also reduce soil aeration, which could inhibit N_2O emissions. Plastic film mulching can indirectly influence soil N_2O emissions by regulating soil moisture, although the mechanisms involved differ. Specifically, during periods of abundant rainfall, film mulching reduces nitrogen leaching from the soil compared to areas without mulching, which promotes N_2O generation through nitrification and denitrification processes. Conversely, in times of scarce rainfall, film mulching similarly reduces nitrogen leaching, resulting in minimal changes to the substrates for soil nitrification and denitrification, and consequently no significant alterations in N_2O emissions. Additionally, film covering significantly elevates the soil temperature. This increase in temperature can enhance oxidation and the number of negative charges on the biochar surface, thereby improving the soil's cation adsorption capacity, forming more organic-mineral complexes, and obstructing cracks and channels within the biochar. Ultimately, this hinders the external diffusion of N_2O [72–74]. Some studies have indicated that there is no significant difference in cumulative N_2O emissions between mulched and non-mulched conditions. This lack of difference is attributed to mulching's role in promoting plant growth and enhancing nitrogen absorption by crops, which reduces soil nitrogen residues [75]. Research suggests that the cumulative N_2O emissions from film-mulched potatoes in dryland conditions are only 56.4% to 72.1% of those in non-film-covered treatments. This finding is linked to a significantly lower gene copy number of AOB in the presence of film compared to circumstances without it [50]. Additionally, research supports the conclusion that mulching decreases soil N_2O emissions by reducing the abundance of AOB-amoA genes [50].

Table 1. Effect of surface mulching on N_2O emissions.

Coverage Methods	Effects on N_2O Emissions	Reference
Plastic film	Increased N_2O emissions from soil nitrogen and temperature increase in radish season and lower emissions from low soil water content in pepper season	(Zhao, M. et al., 2020) [76]
Plastic film	Lower N_2O production in long-term mulched soils attributed to reduced nitrifying microbial activity	(Gao, N. et al., 2023) [77]
Straw mulch	Reduced N_2O emissions without fertilizer compared to fertilizer under straw mulch	(Zhao, Y. et al., 2025) [78]
Plastic film	Increase in soil nitrogen content by cover crop residues compared to no cover contributes to cumulative N_2O emissions	(Kim, G.W. et al., 2017) [79]
Plastic film	Long-term mulching negatively affects microorganisms by reducing N_2O	(Gao, N. et al., 2024) [80]
Bark mulch	Bark mulch as a strategy for mitigating N_2O emission in sandy loam soils of vineyard systems	(Fentabil, M.M. et al., 2016) [81]
Straw mulch	Under high moisture conditions, high straw volume mulching was more effective in reducing N_2O emissions than medium straw volume mulching	(Zhang, Z. et al., 2025) [82]
Straw mulch	A meta-analysis revealed that both straw and mulch increased N_2O emission	(Wang, H. et al., 2021) [83]
Plastic film	Mulching increases N_2O emissions by influencing soil properties	(Nawaz, A. et al., 2021) [84]
Plastic film	Planting rye may reduce soil temperature to suppress N_2O emissions	(Dix, B.A. et al., 2024) [85]
Straw mulch	Straw as a carbon source, prompting nitrogen fertilization to increase N_2O emissions	(Yan, Z. et al., 2024) [86]
Straw mulch	Increase in cumulative N_2O emissions under conventional N fertilization, no effect under optimized N inputs	(Wei, H. et al., 2024) [87]

3.2. Straw Mulching and Returning to Fields

These useful reports have addressed the impact of straw returning to soil on N_2O emissions, indicating promotion [88], inhibition [89], or no effect [90]. The variability in research findings may be attributed to factors such as the hydrothermal conditions of the soil, the soil nutrient levels, microbial activity, and the availability of substrates for nitrification and denitrification processes [91]. Some studies have observed a significant increase in N_2O emissions following the return of wheat or corn straw to fields [92–94]. Conversely, other research has demonstrated a notable reduction in emissions associated with straw return, attributed to the high organic matter and nutrient content of straw, its elevated carbon-to-nitrogen ratio, and its capacity to absorb soil nitrogen, ultimately leading to emission reductions [16]. Additionally, some studies suggest that the influence of straw mulching on N_2O emissions is primarily linked to soil moisture levels and the irrigation system employed [95]. Straw mulching tends to elevate the water content of the topsoil, creating an anaerobic environment that favors the proliferation of soil-denitrifying microorganisms, thereby enhancing surface N_2O emissions [50]. However, another study reported that straw mulching can actually decrease soil N_2O emissions [50]. Furthermore, straw mulching generally induces a cooling effect in the soil, which can alter the activity of soil enzymes involved in the nitrogen cycle and subsequently impact N_2O emissions [96,97]. It has also been observed that straw mulching increases soil carbon sources and enhances the activity of nitrifying and denitrifying bacteria influenced by soil carbon levels [92,93]. Lastly, the addition of straw and biochar to soil has been shown to inhibit N_2O emissions [98]. This phenomenon may occur because straw and biochar

contribute to the formation of humus, carbohydrates, and other macromolecular substances in the soil that are challenging for microorganisms to absorb. In turn, this leads to an increase in the soil's carbon-to-nitrogen (C/N) ratio and enhances the soil's permeability and water retention capacity. Additionally, it inhibits nitrification and denitrification to some extent [99,100]. It was concluded that straw mulching, as a form of organic matter, has a minimal impact on N_2O emissions, with the primary factor influencing N_2O levels being the application of nitrogen fertilizers [101].

The return of straw to fields can significantly influence the types, abundance, and composition of microorganisms related to the nitrogen cycle, with its effects being contingent upon the timing of the return. For instance, the short-term addition of wheat straw has a limited impact on the soil nitrification process. Research indicates that the introduction of wheat, tadpole, and rapeseed straw does not alter the population of soil-nitrifying bacteria. In soils where straw is returned to the field, operational taxonomic units (OTUs) associated with nitrite fixation are relatively abundant, potentially accelerating the soil nitrification process and leading to increased N_2O emissions [102]. A study found that in wasteland soils, the combination of fertilizers and straw enhances the populations of soil nitrogen-fixing bacteria, AOB, and nitrifying bacteria [50]. The addition of organic fertilizers and other organic materials can improve the abundance of specific microorganisms related to soil nitrogen fixation [103], nitrification [104], and denitrification [105]. During the nitrification process, some N_2O is retained in soil moisture or pores, while a portion is utilized by nitrifying microorganisms, which further convert it into molecular nitrogen (N_2). Only the remaining fraction is released from the soil as N_2O. Additionally, straw mulching has varying effects on the abundance of different nitrogen functional genes. Some recent studies have shown that straw cover primarily increases the relative abundance of the AOB-amoA gene and Nitrosospira within AOB, thereby contributing to elevated soil N_2O emissions [50].

4. Prospects and Outlook

This review focuses on the effects of different environmental factors on N_2O emissions which are classified and summarized, and quantitative parameters are provided. While pH > 8.5 accelerated nitrification, pH < 6.0 inhibited denitrifying microbial activity. Temperatures below 5 °C significantly reduced N_2O emissions, and emissions were positively correlated with temperature at 15–30 °C. N_2O emission peaked when the WFPS was 70–80%, and a WFPS > 80% promoted N_2O's reduction to N_2. C/N > 30 inhibited N_2O emission, while C/N < 25 promoted emission. Mulching was more effective in reducing emissions than straw mulching, but the exact effect varied with soil type and climatic conditions. Based on a comprehensive overview, future research directions are proposed:

1. The complexity of the multi-pathway emissions mechanism. The primary mechanism for producing N_2O in farmland is through the nitrification and denitrification processes facilitated by nitrifying bacteria. However, alternative pathways, such as fungal denitrification and chemical denitrification, also contribute to N_2O production. Consequently, the mechanisms and pathways of N_2O generation in agricultural settings remain incompletely understood. This complexity is particularly pronounced when multiple pathways operate simultaneously, making it challenging to isolate the contribution of a single pathway to overall N_2O emissions.
2. The optimization and innovation of coverage measures. The overarching goal of emission reduction efforts is to minimize greenhouse gas emissions without compromising agricultural productivity. Currently, research examining the effects of various mulching methods, mulching materials, straw application rates, and soil amendment

amounts on soil N_2O production and emissions is still relatively limited, highlighting an urgent need for further investigation in this area.

3. Mechanisms of interaction between microorganisms and environmental factors. With the rapid advancement of microbial measurement technologies, the diversity of microorganisms involved in nitrification and denitrification continues to expand. Additionally, numerous environmental factors influence N_2O production in farmland, and these factors interact in complex ways within the soil environment. Therefore, it is essential to employ networked causal analysis mathematical models to elucidate the correlation mechanisms between changes in soil environmental factors and N_2O production, thereby providing a foundation for developing effective N_2O emission reduction technologies in agricultural contexts.
4. Integrated studies of soil–crop–atmosphere systems. Numerous studies have focused on the net emissions of N_2O from farmland into the atmosphere; however, there is a notable paucity of research on the dynamic changes of N_2O within the soil profile and its correlation with crop growth conditions. In this respect, there is an urgent need to enhance comprehensive research on N_2O emissions in the context of the soil–crop–atmosphere continuum.

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Abbreviations

List of abbreviations.

Abbreviation	Full Form
AMO	Ammonia monooxygenase
HAD	Hydroxylamine dehydrogenase
NiR	Nitrite reductase
Nor	NO reductase
NR	Nitrate reductase
N_2OR	N_2O reductase
AOA	Ammonia-oxidizing archaebacteria
AOB	Ammonia-oxidizing bacteria
NOB	Nitrite-oxidizing bacteria
NN	Nitrification by nitrifying bacteria
ND	Denitrification by nitrifying bacteria
NCD	Denitrification coupled to nitrification reactions
HD	Heterotrophic denitrification
WFPS	Water filling pore space
OTUs	Operational taxonomic units

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