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REVIEW ARTICLE

Agronomical interventions to mitigate nitrous oxide (N_2O) emission in agriculture - A comprehensive review

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Abstract

Global warming is a critical global concern that poses a serious threat to human life. The release of greenhouse gases (GHG), including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), is a primary driver of climate change. Among these, N_2O is highly potent, with a global warming potential approximately 300 times higher than CO_2, making it a major contributor to climate change. Its emissions mainly originate from agricultural practices, particularly through soil-based nitrification and denitrification processes. N_2O emissions can be mitigated by identifying sources, calculating the emission and adopting mitigation strategies. Agronomic practices play a crucial role in lowering N_2O emissions while maintaining crop productivity. This review discusses N_2O emission mechanisms in agricultural soils and explores various agronomic interventions, including optimal nitrogen fertilizer application, precise timing of nitrogen application, split application, biofertilizers, fertigation, neem-coated urea, proper management of crop residues, cover cropping, crop rotation and conservation tillage. Studies indicate that proper nitrogen supply timing and application methods can reduce emissions by 30-40 %, while adjustments in tillage and irrigation, along with soil amendments like biochar and lime, can lower emissions by up to 80 %. The use of slow-release fertilizers and nitrification inhibitors can cut emissions by 50 %, while arbuscular mycorrhizal fungi treatment can lead to a reduction of up to 75 %. Additionally, crop rotation and integrated nutrient management enhance mitigation efforts. These agronomic approaches can substantially decrease N_2O emissions from soils, mitigate global warming and support sustainable agriculture.

Keywords: agronomic interventions; global warming; nitrification; nitrous oxide

Introduction

Global warming is a critical global concern that poses severe risks to both human life and the environment. Over the 20th century, the average global surface temperature has risen by approximately 0.6 ± 0.2 °C (1). This temperature increase is mainly attributed to the release of greenhouse gases (GHGs), including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), which contribute to climate change (1). These gases trap infrared radiation, preventing heat from escaping Earth's atmosphere (1). N_2O, colourless, non-toxic gas commonly referred to as laughing gas. N_2O is a powerful greenhouse gas with a global warming potential (GWP) approximately 300 times higher than CO_2 over a span of 100-year (2). Over the last hundred years, there has been an estimated rise of about 20 % in the concentration of N_2O in the atmosphere, which continues to rise at a rate of 0.2 - 0.3 % year^{-1} (3). Furthermore, N_2O plays a major role in ozone layer depletion (3). Since 1997, significant reductions have been made in non-biological N_2O emissions, such as those linked to the transport sector, while emissions from agriculture remain largely unchanged (2). Agriculture remains the predominant contributor to N_2O emissions (Fig. 1), mainly due to nitrogen fertilizer application and organic matter decomposition in soils. Essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are vital for maintaining sustainable global crop yields. Nutrient deficiencies, particularly N and P, limit potential yields, especially in developing regions, where increasing N fertilizer application or promoting biological N fixation is necessary to enhance food security. However, intensifying agricultural practices without effective mitigation measures exacerbates N_2O emissions, leading to environmental degradation. These emissions not only accelerate climate change but also indicate inefficiencies in nitrogen utilization, presenting both economic and ecological challenges (4). Over two-thirds of

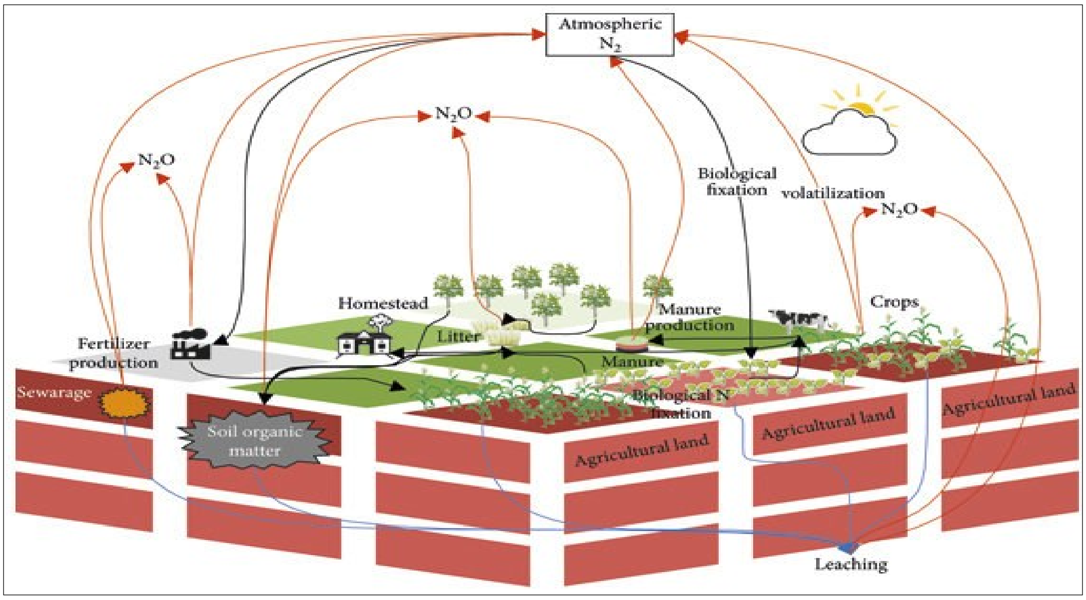

Fig. 1. N_2O transformation process (14).

N_2O emissions arise from biological and chemical soil processes, influenced by factors such as soil moisture, temperature, pH and nitrogen availability (5). Microbial activities such as denitrification (DNF) and nitrification (NF) are the primary pathways for N_2O production. DNF occurs under low-oxygen conditions, converting nitrate (NO_3-) into dinitrogen (N_2), with N_2O as an intermediate product. Conversely, NF is an aerobic process where ammonium (NH_4+) is oxidized to nitrate, producing N_2O under specific conditions (6). N_2O emission can be mitigated by identifying sources, calculating the emission and adopting mitigation strategies. Understanding and mitigating N_2O emissions from agricultural soils is crucial for achieving sustainable agricultural practices. Effective agronomic interventions target these underlying processes to minimize N_2O emissions. Agronomic interventions like application of crop residues, application of fermented organic materials, application of compost, proper tillage practices, irrigation management, application of bio char, integrated nutrient management, selection of Plant Genotypes, application of AMF, fertilizer management and, implementing crop rotation and diversification offer a practical pathway to address this issue. Agronomic interventions are a cornerstone of N_2O mitigation because they are practical, cost-effective and adaptable to diverse agricultural systems. While technological solutions like bioengineering and microbial interventions have potential, they are often complementary to agronomic practices rather than replacements. Agronomic interventions not only for reducing N_2O emissions but also enhancing resource efficiency and guaranteeing the long-term sustainability of global food systems and productivity (7). This review explores various agronomic interventions to mitigate N_2O emissions from agricultural soils, with a focus on their effectiveness, mechanisms and practical implications.

Factors responsible for N_2O production

There are many factors that affect N_2O production (Fig. 2) which are given below

Soil pH

Soil pH plays crucial role in regulating N_2O emissions by influencing the activity of microorganisms involved in NF and DNF (8). In neutral to slightly alkaline soils (pH 6–8), NF (ammonia oxidation) is favoured, producing N_2O as a by-product (9). In acidic soils (pH < 6), DNF becomes more dominant, with N_2O being an intermediate that can accumulate due to reduced activity of the enzyme N_2O reductase, which converts N_2O to N_2 (9). The microbial community structure and its enzymatic activities, which are pH-dependent, significantly affect the extent of N_2O emissions (10).

Soil moisture and soil temperature

High soil moisture levels, particularly in water-filled pore spaces (WFPS), promote N_2O production by accelerating the decomposition of soil organic carbon, which fuels microbial metabolism and activity (11). An abundant carbon supply boosts microbial activity, thereby increasing N_2O emissions. Moist conditions sustain prolonged N_2O release by ensuring a continuous supply of carbon substrates for microbial processes (12). Soil temperature also plays a significant role by interacting with moisture levels to influence N_2O dynamics. Rising temperatures up to an optimal range of 25-35 °C enhance bacterial proliferation, thereby intensifying the activity of both nitrifying and denitrifying bacteria, further impacting N_2O emissions (13).

Soil micro-organisms

A greater soil depth significantly reduces microbial biomass and its activity. The presence of microbial communities is essential for NO_3- and NO_2- reduction, which ultimately leads to the formation of nitric oxide (NO), N_2O, or dinitrogen (N_2). This transformation is closely associated with electron transport during the DNF process (Fig. 3) (14, 15). Under anaerobic conditions, denitrifying bacteria facilitate the conversion of N compounds by utilizing energy derived from light, organic matter, or inorganic substrates, classifying them as phototrophs, organotrophs, or lithotrophs. Some enzymes, such as hydroxylamine oxidoreductase, ammonia monooxygenase and nitrite oxidoreductase, are involved in NF, influencing the rate of N_2O release (16). Similarly, DNF-associated enzymes like nitrite reductase, nitrate reductase, NO reductase and N_2O reductase determine the extent of N_2O emissions (16). The availability of soil organic carbon, in combination with soil moisture, further regulates N_2O

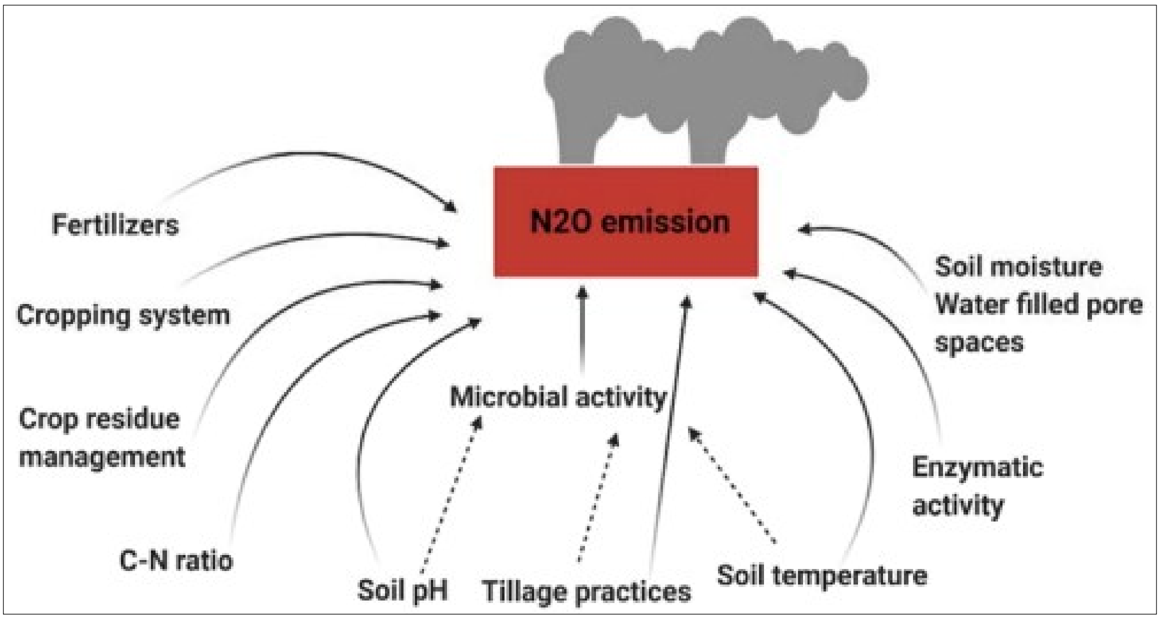

Fig. 2. Factors that produces N_2O (14).

production by providing an essential substrate for microbial proliferation (17).

Soil characteristics

Fine-textured soils generally higher N_2O emit due to their higher capillary pore content compared to sandy soils. These pores retain moisture for extended periods, creating anaerobic conditions that facilitate increased N_2O emissions (18). As soil texture becomes finer and WFPS rises, DNF rates also increase. However, when WFPS declines, DNF slows down (19). In fact, in clay-rich soils, N_2O emissions are significantly elevated when WFPS exceeds 40 % to reaching peak levels at more than 70 % WFPS (19). Soil texture not only dictates whether aerobic or anaerobic conditions dominate but also influences N availability, organic carbon content and microbial populations, all of which affect N_2O emissions (18). Moreover, soil texture influences N_2O emissions by altering soil nitrogen availability, organic carbon content and microbial community composition (16). Field surface morphology also plays a role, with depressions exhibiting higher emissions than ridges or slopes due to increased moisture retention. Lastly, Moreover, high-altitude areas experience greater N_2O emissions because lower atmospheric pressure reduces the resistance exerted on soil surfaces (20).

Application of crop residues

Incorporating crop residues to agricultural soil, which offers quicker available carbon (C) and N, thus becoming a potent source of N_2O production (21). The process of nitrogen mineralization from crop residues contributes to N_2O formation (22), with the rate of release depending on the carbon-to-nitrogen (C:N) ratio of the residues (23). The rate of DNF is influenced by the quantity of C that is readily accessible to the denitrifying bacterial community (24).

Nitrogen application

Prior to the 1950s, a significant share of N_2O emissions originated from livestock-related activities, with N fertilizer contributing less than 50 % of total emissions. However, with rising food demand and intensive agricultural practices, N fertilizer application has increased substantially, making agriculture responsible for over 60 % of total N_2O emissions (25). N fertilizers are highly mobile in the soil and undergo various transformations, including leaching, volatilization,

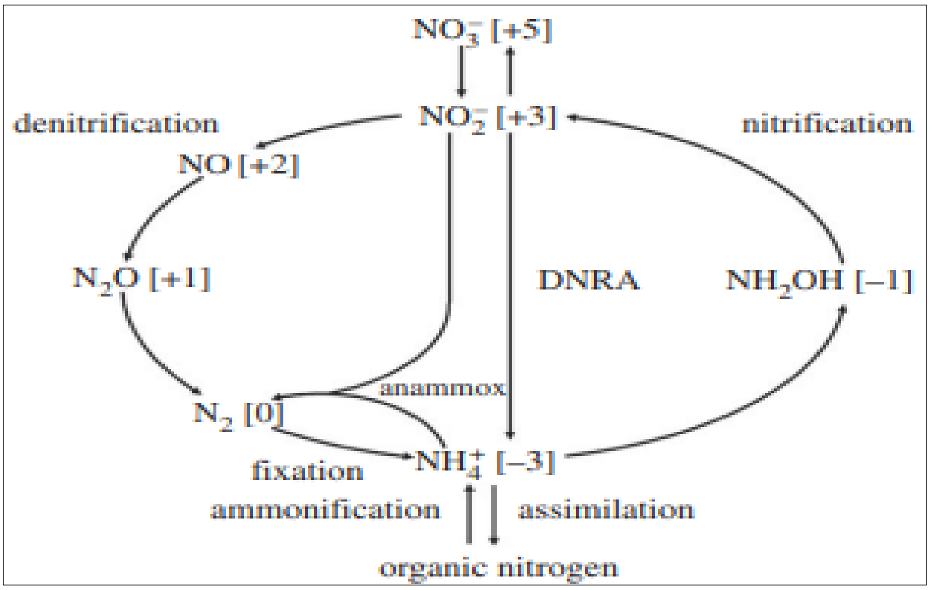

Fig. 3. Microbial nitrogen cycle (14).

immobilization and DNF, all of which contribute to N_2O production (26). The primary sources of N_2O emissions in fertilized soils are NH_4+ and NO_3-, both of which are directly supplied by N fertilizers. The extent of N_2O emissions depend on the type and application method of these fertilizers (27).

Quantification of N_2O in soil

Quantifying N_2O emissions is not very difficult; however, significant spatial and temporal variability at local scales presents considerable challenges (28). Detection of N_2O gas is possible using infrared analysers, gas chromatography with electron capture detectors, tunable diode lasers and molecular sieves (0.5 nm) (29). Two primary methods are employed for N_2O measurement: soil surface chambers used for short-term observations and micrometeorological techniques for long-term observations.

Chamber method

The chamber method is one of the most accessible techniques for measuring N_2O emissions. N_2O flux is captured by static chambers placed in the field, as recommended by Mosier (30). These static chambers consist of two parts (anchor or base and chamber). The anchor, typically made of thin-walled stainless steel, minimizes soil disturbance during setup. The chambers, constructed from non-reactive materials, contain two ports-one for an air thermometer and another for gas sampling. Anchors are inserted 10 cm into the soil at least 24 hrs before the initial gas flux measurement, ensuring proper sealing around the edges to prevent alteration of the soil microclimate that could impact emissions. During sampling, the chamber is placed inverted on the base. Vegetation remains inside the chamber while gas collection occurs (31). Before sampling, verifying the base position and the presence of water in the base rim is crucial. The floodwater level inside and outside the base is recorded, along with soil and chamber temperatures immediately after sampling. Gas samples are collected using a polypropylene syringe inserted into the chamber's septa, with samples taken at three intervals: 0, 15 and 30 min after chamber deployment (32). The time interval will vary depends on the spatial and temporal. A 20 mL sample is usually drawn and transferred to a pre-evacuated 15 ml glass vial, sealed with a grey butyl rubber septum. Overpressure is created by injecting excess gas, making later extraction easier. The collected samples are analysed using gas chromatography (GC) (33).

Micrometeorological methods

Micrometeorological techniques rely on monitoring air masses moving across ecosystems, offering advantages over the chamber method by providing broader spatial and temporal integration. These methods allow for continuous measurement of gas fluxes over areas ranging from 1-10 km^2 to several million hectares. Using sensors mounted on towers, they capture air movement and gas composition, enabling the calculation of flux rates and directions based on concentration gradients and turbulence (34). While micrometeorological approaches may be less sensitive than chamber methods, they are valuable for estimating long-term flux patterns, especially in cases of unpredictable emissions (35). These systems have been deployed at specific sites, demonstrating consistency with chamber-based measurements and providing reliable sensitivity (36). Recent advancements, particularly in Fourier-Transform Infrared Spectroscopy (FTIR), have further improved the capacity to monitor moderate fluxes continuously (37).

Agronomical interventions to mitigate N_2O emission

Irrigation management

Irrigation plays a crucial role in N_2O emissions. The volume and distribution of water significantly influences N_2O emissions due to its impact on soil moisture and the N cycle (38). The alternate wetting and drying (AWD) method can reduce water usage by 70 % and lower CH_4 emissions by 97 % (38). However, in clayey soils, it can lead to a fivefold increase in N_2O emissions due to soil moisture fluctuations. WFPS in soil is a key factor in N_2O production. Peak emissions typically occur when WFPS ranges between 45-90 % (19). In aerobic conditions, NF and DNF dominate N_2O production when WFPS reaches 60-70 % (19). However, when WFPS is around 50-60 %, N_2O generation may be restricted due to dissimilatory nitrate reduction to ammonia (39). For example, frequency flooding in rice fields suppresses N_2O emissions by maintaining saturated conditions that promote nitrate conversion to N_2. In contrast, AWD can elevate N_2O emissions by causing soil cracks and increasing aeration in deeper layers (40). Advanced irrigation techniques such as drip fertigation have potential in minimizing N_2O emissions (33). These methods help maintain optimal WFPS, localize nutrients near the root zone and reduce leaching, which enhances nutrient uptake and limits N_2O formation (41). Sustainable irrigation strategies that regulate soil moisture effectively are essential for mitigating N_2O emissions. Transitioning from conventional practices like flood irrigation to advanced methods such as drip irrigation, sprinkler irrigation, or optimized AWD can contribute to sustainable agriculture while reducing N_2O emissions (41).

Proper tillage management

Tillage practices influence crop productivity and GHG emissions by altering soil properties (42). The impact of tillage on N_2O emissions is inconsistent. In rice cultivation, research observed notable decline in N_2O under no tillage (NT) compared to conventional tillage (CT) (43, 44). Likewise, a meta-analysis covering rice and other field crops such as wheat and maize, indicated that conservation tillage lowers N_2O emissions by approximately 17.8 % in contrast to CT (45). Another meta-analysis highlighted that NT offers benefits in terms of reducing both N_2O and CH_4 emissions, with a 6.6 % reduction compared to CT (46). The prolonged implementation of NT improves soil structure and lowers soil temperature as surface residues reflect incoming radiation and act as an insulating layer between the soil and the atmosphere. Consequently, this results in a reduction in N_2O emissions compared to conventional tillage (CT) (47). It was reported that NT lowers N_2O emissions in irrigated regions but leads to an increase in N_2O emissions in rain-fed areas (48). However, some investigation indicate NT may increase N_2O emissions, particularly in rain-fed areas or under certain conditions like high soil moisture and limited oxygen (49). Climate plays a crucial role in tillage outcomes. In warm, dry regions, NT reduces N_2O emissions, while CT exacerbates them due to organic matter decomposition (50). Despite variations, NT and reduced tillage generally support GHG mitigation and sustainable agriculture by preserving soil organic matter and reducing emissions. Advanced tillage practices tailored to specific conditions optimize GHG reduction and productivity.

Crop residue management

Returning crop residue (CR) to the soil boosts agricultural productivity and enhances soil fertility, though its effect on N_2O emissions varies depending on the characteristics of both the CR and the soil (50). Some studies link CR return to increased N_2O emissions by improving soil aggregation, microbial activity and nutrient availability, which stimulate NF and DNF (51). Conversely, other studies report reduced N_2O emissions when CR with higher C/N ratios immobilize N and decrease NO_3- availability. Soil properties such as pH, texture and moisture content significantly influence the effect of CR on N_2O emissions (52). For instance, fine-textured soils with added CR exhibit increased microbial activity and N_2O emissions, whereas coarse-textured soils show limited DNF due to low organic carbon (53). High water-filled pore space (WFPS) affects oxygen availability in hotspots, altering the N_2O:N_2 ratio during DNF. At high WFPS (90 %), CR may reduce N_2O emissions (54). Seasonal factors and external N inputs also affect CR decomposition and its interaction with N_2O emissions. Residue incorporation in spring, combined with N fertilizers, intensifies microbial activity, increasing N_2O emissions. Proper CR management, considering residue characteristics, soil conditions and timing, can help mitigate emissions.

Use of Organic Amendments (OA)

Organic amendments (OA), including crop residues and animal-based inputs like manures and slurries, are widely utilized to reduce dependence on synthetic N fertilizer use, enhance soil fertility and address environmental concerns (55). However, their impact on N_2O emissions is complex and context dependent. Some researchers show that OA can increase N_2O emissions by providing energy for denitrifies and creating anaerobic micro-sites within soil aggregates, promoting DNF (27). On the other hand, some researchers argue that OAs may reduce N_2O emissions by stimulating microbial N assimilation, which limits the N available for NF and DNF (56). The disparity between these two contrasting behaviors may stem from differences in the application of organic amendments, soil characteristics, climatic conditions and past fertilization practices in the respective studies (56). Long-term studies emphasize that the quantity of organic amendments used is a key factor in carbon accumulation and its subsequent impact on N_2O emissions (57).

Composting

Composting involves the decomposition of organic matter under aerobic conditions, transforming it into nutrient-rich material (58). Applying compost in crop production is a widespread practice, where the dissolved organic carbon (DOC) derived from composted manure acts as a carbon source for microbial DNF, thereby affecting N_2O emissions (5). Vermicomposting, which relies on earthworms to produce nutrient-enriched compost, enhances soil structure and microbial activity. A study on rice indicated that vermicompost application reduces NH_4+ and NO_3- leaching into water (59). However, excessive vermicompost use may lead to elevated N_2O emissions due to increased N availability and heightened microbial activity (59). Moreover, the combination of vermicompost with synthetic fertilizers may further escalate N_2O emissions by increasing NO_3^- concentrations. In contrast, integrating biochar with vermicompost improves the C/N ratio, and lowers N_2O emissions. The co-application of biochar and vermicompost has shown potential in mitigating N_2O emissions while improving soil health (59). Composted manure can reduce N_2O emissions and enhance carbon sequestration, though it may also contribute to CH_4 emissions (60). Research on rice has shown that compost application can lower N_2O emissions by over 50 % compared to urea-based fertilization (61). Furthermore, composted rice straw has been found to significantly decrease both CH_4 and N_2O emissions compared to fresh straw (62). More extensive research is required to fully understand the mechanisms underlying these effects and optimize strategies for emission reduction. Using composted materials seems to be an effective strategy for enhancing soil characteristics while also minimizing N_2O emissions.

Application of fermented organic manures

Fermentation involves the decomposition of organic materials under anaerobic conditions, producing energy and by-products. Incorporating fermented organic manures into the soil can help mitigate greenhouse gas (GHG) emissions by breaking down organic matter during the fermentation process (63). However, in irrigated soils, their application can elevate N_2O emissions due to increased substrate availability, enhanced microbial activity and the formation of micro-sites (64). Additionally, high rainfall conditions can further contribute to N_2O emissions in soils treated with manure. To optimize productivity while minimizing emissions, the use of fermented organic manure in irrigated and high-rainfall regions should be carefully regulated to support climate-resilient agroecosystems (65).

Biochar application

Biochar, a carbon-dense substance obtained through the pyrolysis of organic material, has considerable potential for enhancing soil quality (Fig. 4) and mitigating greenhouse gas (GHG) emissions (66). When incorporated into soils, biochar sequesters carbon for extended periods, with plant-derived biochar persisting for up to 2000 years. This long-term carbon sequestration makes it an effective tool in combating global warming (66). The application of biochar reduces emissions of N_2O (Table 1). Factors like soil moisture and environmental conditions significantly influence these outcomes. Despite these complexities, biochar's potential for reducing N_2O emissions and improving soil fertility makes it a promising long -term strategy when suitable environmental conditions exist.

Application of Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) establish mutualistic relationships with plants, playing a significant role in N cycling and potentially reducing N_2O emissions (75). AMF facilitate nutrient uptake for host plants, reduces NO_3-, leaching and lowers N availability for N_2O production pathways, such as NF and DNF (75). By preferentially absorbing ammonium (NH_4+), AMF competes with other soil microbes, thereby reducing the substrates available for N_2O producing organisms (76). Research indicates that AMF can lower N_2O emissions in various soils and crops, including rice. This reduction may result from direct AMF activity or from physiological changes in AMF-colonized roots. AMF reduce ammonia-oxidizing bacteria (AOB) populations by lowering NH_4+ in the hyphosphere, further decreasing N_2O production. Additionally, AMF activity lowers the presence of genes associated with N_2O production (76). By regulating soil N forms and limiting NO_3- and NH_4+ availability, AMF contribute to lowering N_2O emissions, underscoring their ecological importance in sustainable agriculture.

Fertilizer management

Optimizing N and P fertilizer use improves crop productivity while mitigating greenhouse gas (GHG) emissions. The release of N_2O from soils is influenced by fertilizer type, rate and application timing (77).

Right quantity: Maintaining N at the lowest effective levels reduces soil N availability and associated N_2O emissions (77). Studies show that increasing N fertilizer rates raises N_2O emissions, although emissions vary by N source. In rice systems, experiments have shown that reducing N use by 33 % resulted in a 28 % decline in N_2O emissions (78). Aligning fertilizer application with crop nutrient needs and implementing split applications at various growth phases can further enhance nitrogen use efficiency (NUE) while minimizing residual soil N, ultimately reducing emissions (79).

Right time: The timing of N application plays a vital role in mitigating N losses. Applying fertilizer at the right stage significantly decreases N_2O emissions (80). Delaying N application by a few weeks post-sowing, rather than applying it beforehand, allows the crop to absorb more N, minimizing losses to air and water. For instance, applying N as a side dressing during the V-6 growth stage in maize has been shown to enhance NUE and decrease N_2O emissions (81). On the other hand, applying fertilizers or manure in autumn can lead to higher nitrate and N_2O losses (82).

Right place: Deep placement of N fertilizers, as opposed to traditional application methods, improves nutrient availability during later growth stages and reduces N_2O emissions (83). Positioning nitrogen closer to plant roots, such as employing urea banding rather than broadcasting or side banding in wheat and canola, substantially lowers emissions (84). In another Study in maize have reported that deep placement of fertilizer significantly reduced N_2O emissions compared to shallow application (84). Similarly, in lowland rice systems, deep N fertilizer placement reduced N_2O emissions by 80 % in comparison to surface spreading, as it helped retain N in the soil for a longer duration (85). Previous research studied that deep placement supports microbial consumption of N_2O, further reducing emissions, particularly in sandy soils. Overall, deep placement shows promise for reducing N_2O emissions, but its effectiveness depends on specific environmental and management factors (86).

Right type: Fertilizer type significantly influences N_2O emissions, depending on the timing, amount and composition of the fertilizer (77). Fertilizers affect N_2O emissions due to differences in content of NH_4^+, NO_3^- and organic carbon. the application of

Table 1. Applications of bio char on mitigating N_2O emission (14)

Bio char application	N_2O mitigation potential (%)	Reference
Bamboo biochar: 5 tons/ha	38	
Bamboo biochar: 10 tons/ha	48	(67)
Bamboo biochar: 15 tons/ha	61	
Rice and cotton husk biochar: 50tons/ha	36	(68)
Maize stalk biochar: 16.77 tons/ha	10.8	(69)
Bamboo biochar: 5 tons/ha	24.25	
Bamboo biochar: 15 tons/ha	30.7	(70)
Rice straw biochar: 44.8 tons/ha	235.1	
Rice straw biochar: 36 tons/ha	50	(71)
Rice straw biochar: 72 tons/ha	83	
Wood shaving biochar: 10 tons/ha	101.68	(72)
Cotton stalk biochar: 9 tons/ha	46.3	(73)
Cotton stalk biochar:13 tons/ha	33.3	
Rice straw biochar: 1%	82.28	(74)
Rice straw biochar: 5%	185.21	

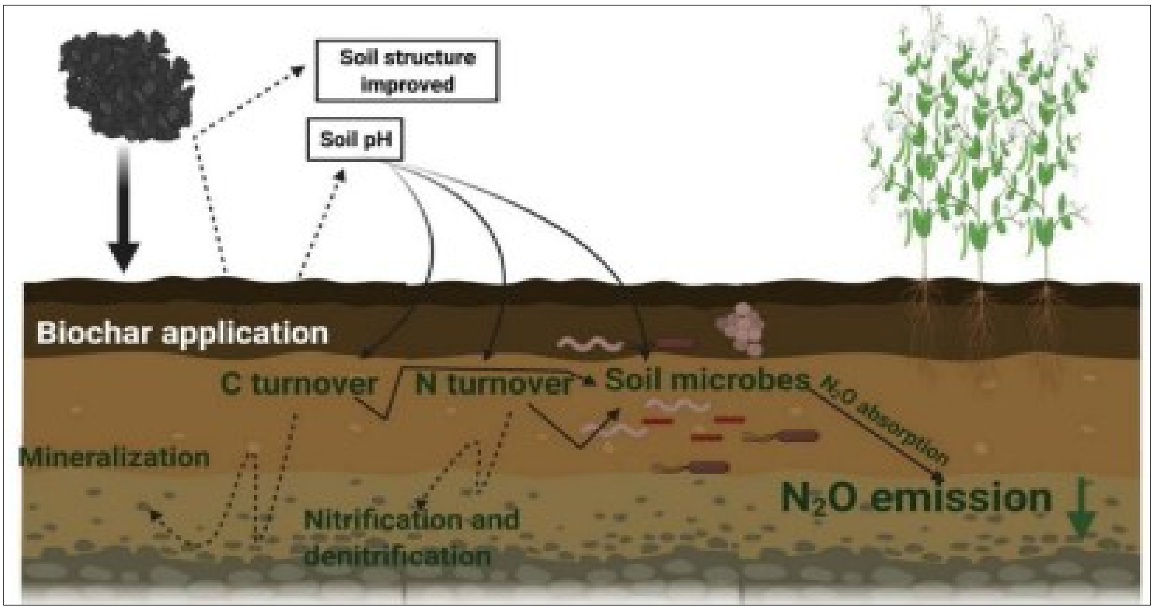

Fig. 4. Role of bio char application in mitigation N2O emission (14).

slurry and urea increased N_2O emissions by 46 % and 33 %, respectively, in maize-wheat rotations compared to control plots (87). Similarly, in wheat systems, urea application has been associated with a 17.4 % increase in emissions at an N rate of 100 kg N ha^{-1} (80). It was also observed that higher application rates, such as 400 kg N ha^{-1} of calcium ammonium nitrate (CAN), resulted in greater emissions compared to 200 kg N ha^{-1} (88). Fertilizers like ammonium nitrate produce higher N_2O emissions, especially in wet soils with high organic matter. In another work, it was shown that substituting urea with ammonium sulfate resulted in increased N_2O but decreased CH_4 emissions (60). However, variability in N_2O emissions among different fertilizers is also influenced by soil characteristics, such as pH, bulk density, texture, microbial activity and organic carbon levels. To meet rising global food demands while minimizing emissions, adopting precision fertilizer management strategies is essential. This includes selecting appropriate fertilizer types, optimizing application rates, ensuring correct timing and employing efficient placement methods. These measures collectively enhance NUE, reduce environmental impact and support sustainable agricultural practices.

Use of nitrification inhibitors or slow-release fertilizer

Nitrification inhibitors (NIs) and slow-release fertilizers play a crucial role in minimizing emissions of N_2O and CH_4 (89). NIs directly reduces N_2O emissions by suppressing NF and indirectly by limiting NO_3- availability for DNF, without affecting crop yields (6). These inhibitors contain chemical compounds that deactivate ammonia monooxygenase (AMO), an enzyme involved in the initial stage of NF. As a result, ammonium (NH_4+) remains in the soil for a longer duration, slowing down NF and limiting substrate availability for denitrifying microbes, thereby reducing N_2O emissions (90). Similarly, slow-release fertilizers, particularly controlled-release fertilizers (CRFs), enhance NUE and minimize N losses. Coated granules in CRFs allow a gradual nutrient release, aligning with crop uptake patterns and curbing N_2O emissions (90). Both NIs and CRFs contribute to emission reduction and improved crop productivity by preventing excessive N supply, which typically drives emissions.

Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) combines organic amendments with inorganic fertilizers to optimize NUE and mitigate N losses by synchronizing soil nutrient availability with plant demand (91). Its impact on GHG mitigation, particularly N_2O, has been studied, though extensive field data remains limited. Previous study observed that integrating compost with NPK fertilizers lowered N_2O emissions compared to using either component alone, especially when compost with a carbon-to-nitrogen (C:N) ratio below 20 was applied (92). Slow decomposition and nutrient release from such organic materials help suppress N_2O formation (92). Another study suggested that organic amendments with lower C:N ratios decrease N_2O emissions when applied alone, whereas amendments with higher C:N ratios are more effective when combined with inorganic fertilizers (93). The influence of organic amendments (OA) on N_2O emissions varies, as it depends on factors such as amendment type, C:N ratio and synthetic N application rates. Organic inputs with high C:N ratios (>20) can immobilize nutrients, reducing N availability for DNF and thereby lowering emissions. Conversely, amendments with low C:N ratios decompose rapidly, releasing N and carbon, which can intensify microbial activity and increase emissions (94). The total N application rate from both organic and synthetic sources also impacts N_2O emissions. Generally, INM approaches using high N rates from a mix of organic and inorganic sources result in higher emissions compared to their lower-dose alternatives (95). However, applying N in equal parts from both sources can reduce emissions relative to using either one exclusively at the same total N rate (96). A meta-analysis indicated that using OA with very low C:N ratios (<8) as a substitute for synthetic N applications has strong potential to lower N_2O emissions (97). Thus, integrating inorganic N with OA containing lower C:N ratios prevents both excessive N mineralization and microbial stimulation from carbon-rich substrates, both of which contribute to N_2O release. Effective INM strategies for reducing emissions must be customized to specific field conditions. No single management practice, including INM, can substantially mitigate N_2O emissions unless reducing GHG emissions is a primary goal in agricultural systems. Achieving meaningful reductions requires integrating INM with broader crop production strategies designed to minimize emissions.

Implementing crop rotation and diversification

Shifting from conventional puddled transplanted rice (TPR) to direct-seeded rice (DSR) serves as a practical approach to reducing GHG emissions. DSR has been found to reduce GWP by 53 % compared to TPR, mainly by reducing CH_4 and N_2O emissions when redox potential is maintained between 100-200 mV (98). Crop rotation and diversification further influence GHG emissions, but their effects vary depending on soil conditions, climate, crop species and management strategies. For instance, rotating maize with other crops has been shown to reduce both N_2O and CO_2 emissions compared to continuous maize cultivation, largely due to reduced N fertilizer inputs in rotational systems (99). While maize-soybean rotations generally produce similar CH_4 emissions, they can lower N_2O emissions compare to monoculture systems due to lower N application rates (99). However, in certain crops like wheat, studies have found no significant differences in N_2O emissions between monocropping and rotation systems. In contrast, grasslands often exhibit higher N_2O emissions due to manure application and animal excreta. The overall impact of cropping systems on GHG emissions is influenced by multiple variables, including soil properties, climate conditions, crop choices and management practices. While crop rotations can help reduce emissions in some scenarios, optimizing N fertilization and planting strategies remains essential for minimizing N_2O emissions.

Policy and socioeconomic aspects of N_2O mitigation

Global initiatives like the Kyoto Protocol and Paris Agreement emphasize reducing N_2O emissions, a potent greenhouse gas, through sustainable agricultural practices (1). These agreements encourage countries to adopt mitigation strategies, such as improved fertilizer management and precision farming, to meet emission reduction targets (4). Economic incentives, including subsidies, tax breaks and grants, play a crucial role in promoting low-N_2O practices. For instance, governments and organizations often provide financial support to farmers transitioning to organic farming (98). However, small-scale farmers face adoption barriers due to high upfront costs, lack of access to technology and limited awareness of mitigation practices. Carbon markets offer a promising solution by enabling farmers to earn carbon credits for reducing emissions, which can be sold to industries seeking to offset their carbon footprint. This not only finances sustainable agriculture but also incentivizes climate-friendly farming practices globally (1).

Knowledge gaps and future research directions

While short-term study provides valuable insights, long-term field experiments are crucial to understand the sustained efficacy of agronomic interventions (7). These studies should evaluate the impact of practices like crop rotation, cover cropping and precision fertilization under varying climatic and soil conditions to ensure scalability and adaptability (99). Another promising but understudied area is the role of soil microbiomes in reducing N_2O emissions. Future research should aim to identify and develop microbial communities that improve N_2O reduction processes, like DNF and NI, without harming soil health (16) Additionally, integrating climate-smart agricultural practices, such as agroforestry and conservation tillage, can mitigate N_2O emissions while enhancing resilience to climate change. Research should focus on measuring the additional benefits of these practices, including better soil health and increased carbon storage (100). The relationship between soil carbon sequestration and N_2O emissions is complex and varies depending on the context. Future studies should explore how practices like organic amendments and reduced tillage influence both carbon storage and N_2O dynamics, ensuring that mitigation strategies do not inadvertently increase emissions. Addressing these knowledge gaps, future research can provide a robust foundation for developing effective, scalable and sustainable N_2O mitigation strategies in agriculture (100).

Conclusion

N_2O emissions from agricultural activities are a crucial contributor to GWP and climate change. Mitigation strategies, such as optimizing N fertilizer application, adopting conservation tillage and employing biochar, slow-release fertilizers and NIs, have shown substantial potential to reduce emissions. These agronomic interventions not only minimize N_2O emissions but also support sustainable agricultural productivity. Implementing these practices globally can play a vital role in addressing climate change while maintaining food security. Continued research and adoption of innovative practices enhance mitigation efforts and achieve long-term sustainability.

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Authors' contributions

ASS carried out the literature review and drafted and edited the manuscript. TR and SR helped in final editing in manuscript. SK and KS participated in the sequence alignment and drafted the manuscript. AM done plagiarism checking and correction. All authors read and approved the final manuscript.

Compliance with ethical standards

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