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REVIEW ARTICLE

Nitrogen management and nitrous oxide emission from agriculture: Implication for climate change

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Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential approximately 298 times that of carbon dioxide over a 100 -year period. Agriculture is a major contributor to global N_2O emissions, primarily using nitrogen (N) fertilizers and associated soil microbial processes such as nitrification and denitrification. This review synthesizes current knowledge on the mechanisms of N_2O production, the influence of soil physical, chemical and biological properties and the impact of nitrogen management practices on emission dynamics. It explores the effects of fertilizer types, application rates, timing and placement on N_2O fluxes, alongside emerging technologies such as enhanced-efficiency fertilizers and nitrification inhibitors. The review also highlights mitigation strategies including conservation tillage, optimized irrigation, crop rotations and integrated nutrient management. Understanding the complex interplay between agronomic practices and N_2O emissions is essential for designing climate-smart agriculture that sustains productivity while minimizing environmental impacts. Hence this paper focus on role of nitrogen mitigation on nitrous oxide emission and implication for climate change.

Keywords: agriculture; implication; mechanism; mitigation; nitrous oxide emission; sources

Introduction

Climate change is one of the pressing global challenges today (1). Changes in the atmospheric concentrations of greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have been linked to rising global temperatures. Major source from enteric fermentation in livestock (45 % of agricultural emissions) and rice cultivation CO_2 (2), Agricultural soils are responsible for approximately 70 % of global anthropogenic N_2O emissions, primarily due to nitrogen fertilizer application and manure management (3) and emitted through soil respiration, land-use changes and the burning of agricultural residues CO_2 (4). The top emitters include the United States, China and India, with India contributing between 10 % and 26 % of global CO_2 emissions by 2100 under various scenarios (5) . India's GHG emissions are projected to grow, with a significant share coming from energy (68 %), industry (20 %) and agriculture (9 %) (6). Agriculture significantly contributes to climate change through greenhouse gas emissions (7) particularly nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 298 times that of carbon dioxide (8). These increased concentrations lead to global warming by amplifying the greenhouse effect. A study explains that soil characteristics significantly impact GHG exchange and emissions (9). Furthermore, research have shown that a variety of factors influence the rates at which greenhouse gases (GHGs) are produced and released from the soil surface (10). These factors include soil temperature, moisture content, climate, tillage practices, fertilization techniques, crop density and the presence of nutrients and organic matter (11, 12). Nitrogen fertilizer application is a primary driver of agricultural N_2O emissions, a potent greenhouse gas contributing to climate change. Recently a novel nitrogen management strategy had evolved in wheat-maize rotation systems involves optimizing nitrogen allocation between crops, increasing inputs to wheat while reducing them for maize. This approach, combined with limited irrigation, increased yields by 1.9-5.7 % and reduced GHG emissions by 55-68 kg CO_2-eq ha^{-1} (13) and in maize production, suitable utilization of fertilizers (SU) and emission reduction treatments (ER) significantly reduced GHG emissions without affecting yields, which demonstrating the effectiveness of optimized nitrogen application (14). However, fertilizer-induced GHG emissions account for the majority of agricultural emissions (15). The application of nitrogen fertilizers can increase N_2O emissions by up to 120 % and CH_4 emissions by 32.5 % (16). Higher levels of soil organic matter can enhance GHG emissions (17). The relationship between nitrite accumulation and N_2O emissions is crucial, as microbial communities respond variably to nitrogen inputs, affecting emission rates in soil (18). The two main microbial processes responsible for producing NO and N_2O are nitrification and denitrification (19). Research on the effects of soil type, land cover and climate on emissions of nitrous oxide (N_2O) and nitric oxide (NO) is still ongoing (20).

In this context aims to critically synthesize current knowledge on the relationships between nitrogen management practices and N_2O emissions in agricultural systems and to evaluate their implications for climate change mitigation. It highlights effective strategies to optimize nitrogen use efficiency (NUE) and agronomic practices while minimizing environmental impacts. Despite numerous studies addressing N_2O emissions, inconsistencies remain due to variability in soil types, climatic conditions and cropping systems. Moreover, there is a lack of integrated understanding of how different nitrogen sources, when combined with other agronomic practices (e.g., no-tillage, cover cropping), affect N_2O fluxes over time. This review addresses this gap by exploring the interactive effects of nitrogen management practices on N_2O emissions under diverse agroecosystems, with a particular focus on their climate implications.

Microbial influence on N_2O emission

Nitrous oxide emission (N_2O), a strong greenhouse gas, affects global warming and ozone depletion (21). Soil microbial communities play a central role in regulating N_2O production and reduction making them critical for emission control. Understanding and managing microbial processes such as nitrification and denitrification is essential for developing effective nitrogen management strategies, as these microbial pathways are central to regulating N_2O emissions and mitigating agriculture's impact on climate change. Microbial metabolism produces N_2O as a byproduct of nitrification and denitrification (22). In soil, nitrification is a crucial process. It is essential to the synthesis of N_2O and entails the oxidation of ammonia (NH_4^+) to nitrate (NO_3^-) (Fig. 1). Microorganisms that are heterotrophic or autotrophic both contribute to nitrification. Microbial processes such as nitrification and denitrification are the primary biological pathways responsible for nitrous oxide (N_2O) production in agricultural soils. Ammonia-oxidizing bacteria (AOB), including *Nitrosomonas* and *Nitrosospira*, oxidize ammonia (NH_3) to nitrite (NO_2^-) during nitrification and can produce N_2O as a byproduct under suboptimal oxygen conditions (23). Similarly, ammonia-oxidizing archaea (AOA), such as *Nitrososphaera*, contribute significantly to nitrification, especially in low-ammonium or acidic soils and have been recognized as important N_2O producers in such environments (24). Denitrifying bacteria, including genera like *Pseudomonas*, *Paracoccus*, *Bacillus* and *Alcaligenes*, facilitate the stepwise reduction of nitrate (NO_3^-) to molecular nitrogen (N_2) under anaerobic conditions, with N_2O being a key intermediate (25). Additionally, recently discovered complete ammonia oxidizers (comammox), such as *Nitrospira inopinata*, are capable of oxidizing ammonia directly to nitrate within a single organism. Interestingly, studies suggest comammox may produce less N_2O than traditional AOB (26). Conversely, some bacteria possessing the *nosZ* gene, like *Cloacibacterium* spp., can consume N_2O, reducing it to N_2 and thus acting as sinks for this potent greenhouse gas (27). A comprehensive understanding of these microbial groups is crucial for developing nitrogen management strategies that minimize N_2O emissions and contribute to climate change mitigation. In acidic soils, heterotrophic bacteria and fungi can encourage nitrification. In Western European coniferous woods, nitrification is facilitated by heterotrophic bacteria and fungus (28). The *Arthrobacter* genus of bacteria seems to be particularly well-suited to heterotrophic nitrification (29) and it is efficient through oxidize ammonium using organic carbon sources, possesses diverse enzymes for nitrogen transformation.

In contrast, denitrification is an anaerobic process regulated by the availability of carbon (C) and nitrate, along with fluctuating oxygen levels (30). In nitrifier denitrification, a

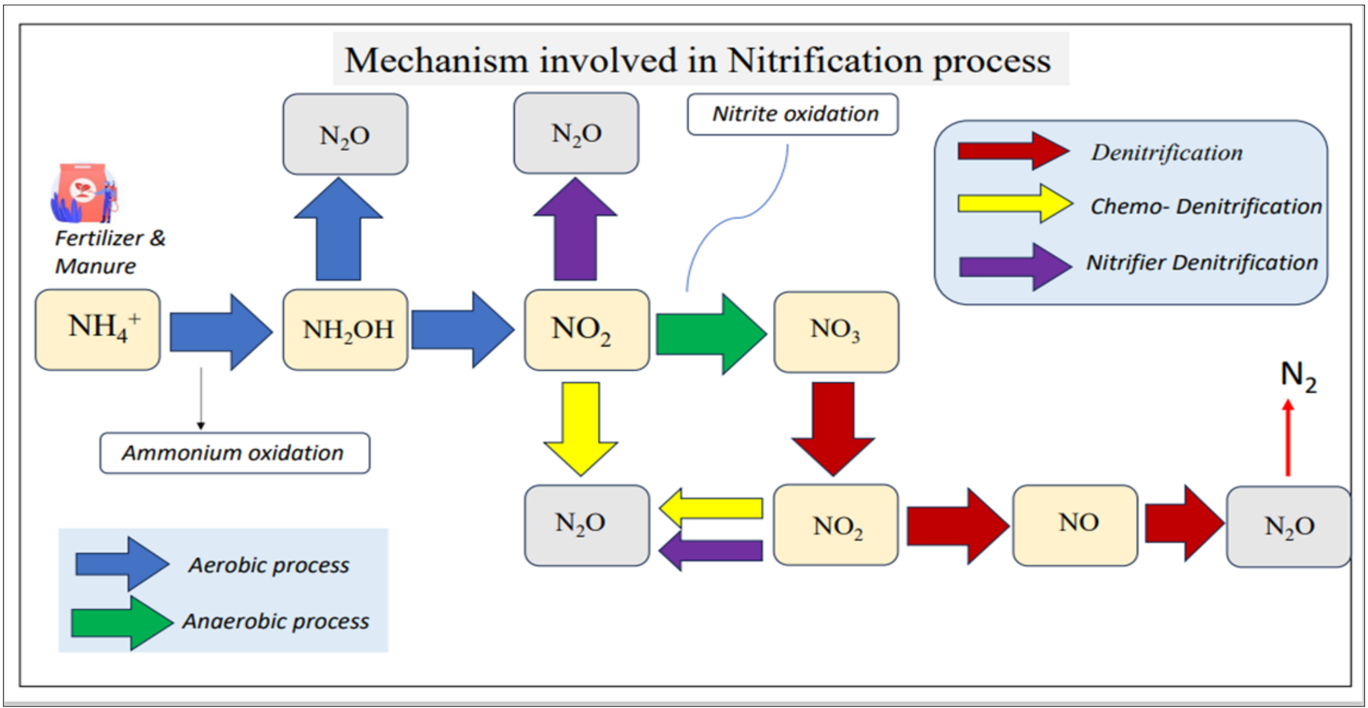

Fig. 1. Processes and enzymes involved in N_2O production.

single group of microbes (e.g., AOB) carries out both ammonia oxidation and nitrite reduction to N_2O (31). The multiple studies demonstrated increased N_2O production via nitrifier denitrification as soil oxygen levels decline (32). The oxygen concentration dropped from 21 % to 3 %, N_2O production increased by 19-fold has been found in the previous study (31). At lower oxygen levels (3 % and 0.5 %), the contribution of nitrifier denitrification to total N_2O emissions ranged between 48 % and 66 % in urea-treated soil and between 34 % and 57 % in soil treated with ammonium sulfate. In comparison, heterotrophic denitrification accounted for 34-44 % and 43-50 % of total N_2O production in these respective treatments. The enhancing soil aeration and selecting appropriate nitrogen fertilizers or nitrification inhibitors based on soil characteristics and environmental conditions could help mitigate N_2O emissions from fertilizers has been suggested. Specifically, they advised against using urea in soils prone to low oxygen availability and acidic conditions (34).

Factors affecting N_2O emission in agriculture

Physical mechanical, chemical and biological features have a complex impact on soil greenhouse gas concentrations (35). Soil moisture, temperature, structure, porosity, organic matter, mineralogy, pH and nitrogen were the factors that caused direct impacts in N_2O emission (36). Rising soil temperatures result in increased CO_2 emissions (34). Even though biological activities are thought to be primarily responsible for N_2O generation and emission, soil physical factors also have a substantial influence (37). The physical, chemical and biological properties that cause major influence in N_2O emission are mentioned below.

Soil physical properties and N_2O emissions

Temperature, compaction, texture and moisture content are the important physical attributes of soil (38). Soil temperature strongly affects N_2O emissions, impacting microbes like *Pseudomonas* (39). Nitrification peaks at 20-35 °C, with some studies showing peaks at 35-40 °C or 38 °C, which is the ideal temperature for nitrification (40). In general, the processes of nitrification and denitrification are temperature-dependent and intensify as soil temperature rises (41). Denitrification peaks at 40-60 °C, varying by climate. In southwest Australia, N_2O emissions peaked at 35 °C but declined above due to increased N_2 production and N_2O reduction (42) and differences in soil type have a greater influence on the amount of N_2O emissions from nitrified N (40). Therefore, sand-free soils release less N_2O than finer-textured clay soils (43). Texture determines N_2O emission whether anaerobic (low oxygen) or aerobic (high oxygen) conditions (43, 44). Site exposure affects N_2O emissions; moist depressions promote production, while low air pressure at higher elevations aids release (45, 46).

Soil compaction greatly impacts N_2O emissions by reducing aeration, especially in damp soils with high bulk density or machinery-induced compaction. Mild compaction can raise N_2O emissions by 20 %, while severe compaction may quadruple them (47). Compaction can reduce soils' ability to either absorb or oxidize atmospheric CH_4 (methane) by as much as 30-90 % (48). Clay soil compaction increases N_2O release, impacts root growth, disrupts microbes, reduces aeration and affects soil health and nutrient absorption (49) and in terms of water-filled pore space (WFPS), The soil has more than 60 % (WFPS), N_2O is released most quickly (50, 51). When WFPS exceeds 60 %, soil pore water replaces oxygen, creating anaerobic conditions that promote N_2O production. Facultative anaerobes like *Pseudomonas citronellolis*, *Paracoccus*, *Bacillus*, *Alcaligenes* and *Denitratisoma* convert NO_3^- to NO_2^-, N_2O and finally N_2 (45, 46, 50). Research revealed that at 70 % WFPS, denitrification is the only process that releases N_2O. Nitrification is the primary mechanism that produces N_2O at 35-60% WFPS (52). More N_2 is produced when N_2O is consumed in anaerobic environments. Research shows that as soil moisture drops, the $N_2O/(N_2O+N_2)$ ratio remains above 60 % WFPS. N_2O emissions peak at ~80 % WFPS (51). Soil physical properties such as texture, structure, moisture content and aeration play a critical role in regulating nitrous oxide emissions, highlighting the need to consider these factors in nitrogen management strategies aimed at reducing greenhouse gas emissions from agricultural systems. The physical and chemical characteristics of soil discussed (Fig. 2), it indicates that the water content shows higher amount of N_2O about 46 % when compared to other factors (53).

Soil chemical properties and N_2O emission

Soil chemical properties play a crucial role in influencing nitrogen transformation processes and subsequent nitrous oxide (N_2O) emissions. At pH below 4.5, autotrophic nitrification is inhibited (54). Denitrification rates decrease with a drop in soil pH. For instance the increase denitrification as pH rose from 5.1 to 9.4 has been observed (36). In general, it is difficult to generalize about the link between pH and denitrification (55). At pH < 6.0, *Pseudomonas* and other denitrifiers emit more N_2O than N_2. At pH 6.0, emissions are roughly equal, while higher pH favors N_2 production (56). Managing soil pH is crucial for sustainable production and N_2O mitigation. In agricultural soils, nitrification, N_2O emissions and N inputs are linked. N_2O substrates come from residues, legumes, manures and fertilizer (57). Soil NO_3^- concentration varies due to nitrification, plant uptake, microbial immobilization and NO_3^- movement (58). Recent studies confirm a positive relationship between nitrification rates and nitrogen uptake by plants. However, N_2O emissions resulting from nitrification vary depending on the type of soil and temperature (59). In the sand and silt loam soils of California, studies conducted (60) and revealed that, soil with the highest NO_3^--N (277 μg g^{-1}) inhibited N_2O reductase, lowering the N_2/N_2O ratio and favoring N_2O production. Managing NO_3^- dynamics and N inputs helps reduce N_2O emissions. Thus, optimizing soil chemical properties such as pH and nitrogen availability is essential for regulating microbial processes and effectively reducing nitrous oxide emissions in agricultural systems.

Biological properties and N_2O emission

The majority of autotrophic bacteria that produce nitrification are *Nitrobacter* and *Nitrosomonas* (61). Nitrification requires aerobic conditions, denitrification involves lithotrophs, organotrophs and phototrophs, with *Pseudomonas* as key soil denitrifiers in anaerobic condition (62). They use organic carbon-based substrates to convert nitrate to N_2 or N_2O. Denitrification occurs in anaerobic (low oxygen) settings. *Pseudomonas denitrificans* effectively removes nitrate, producing N_2 slowly in anaerobic conditions

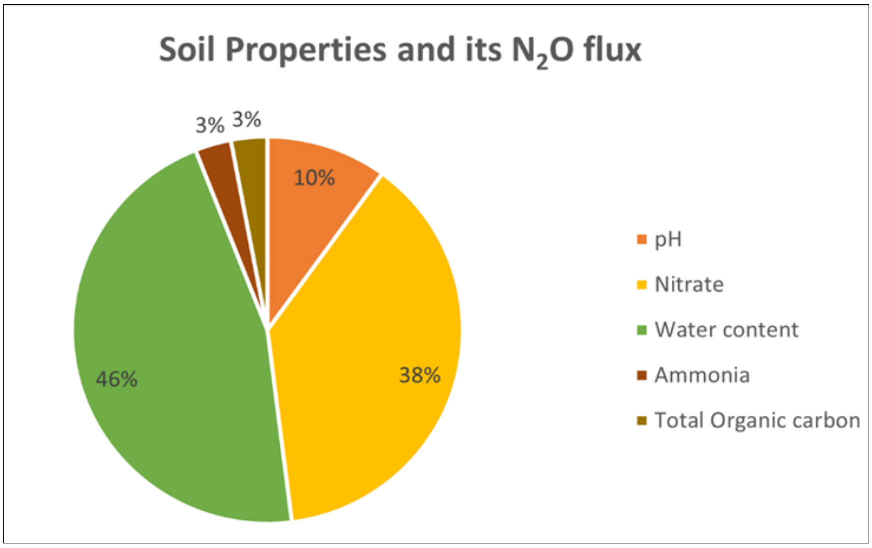

Fig. 2. Comparison of soil physical properties on N_2O flux.

was studied (63). Denitrification depends on microbial activity, C/N ratio (optimal at 5-22), organic carbon availability and environmental factors. Dissolved oxygen (0-4.68 mg/L) and salinity also (0-30 g NaCl/L) influences this process (64). Soil biological properties are fundamental in driving nitrogen transformations, making their management crucial for mitigating nitrous oxide emissions and promoting sustainable agricultural practices.

Fertilizer sources

Organic fertilizers: In addition to providing labile carbon molecules, organic fertilizers are a significant source of inorganic nitrogen (N) in both ammonium (NH_4^+) and nitrate (NO_3^-) forms. These substances increase the heterotrophic denitrifying microorganisms' activity in the soil (65). Organic fertilizers provide a range of carbon molecules, varying in their chemical composition from refractory to labile. During the mineralization process, these substances can be used by soil microorganisms, increasing microbial growth rates and biomass (66).

Inorganic sources: The mineralized nitrogen resulting from the decomposition of soil organic carbon (SOC) during the growing season can be estimated using the following equation (Eqn. 1)

$$M_N = E_{CO2}/R_{C:N} \quad \text{(Eqn. 1)}$$

Where M_N represents the mineralized nitrogen. E_{CO2} is the cumulative CO_2 emission in an N-unfertilized and unplanted subplot. $R_{C:N}$ denotes the soil carbon-to-nitrogen ratio (67) and Table 1 shows the organic, inorganic fertilizer and inhibitors shows impact in N_2O emission in environmental sustainability.

A study has been examined with three approaches for calculating the amount of N_2O produced by granular N fertilizers put to field soil (74). Urea produces more N_2O emissions than conventional fertilizers, with the amount of N_2O production decreasing in the following order: urea > ammonium sulfate ($(NH_4)_2SO_4$) > ammonium nitrate (NH_4NO_3) > calcium nitrate [$Ca(NO_3)_2$] (74, 75). The increased emissions from NH_4-based fertilizers could be caused by either NO_2 buildup or N_2O production during nitrification (76). Three year worth of N_2O emissions from three different cropping systems were studied recently in Colorado (77) reported emission rate, is 26 % less than the current IPCC emission factor, was 0.0074 kg N_2O-N per kilogram of N applied (77). During the course of a three-year study including four cropping systems, the fraction of applied N lost as N_2O varied from 0.4 % to 3.5 % has been discovered (78). Inorganic nitrogen sources, when applied judiciously with appropriate timing and rate, play a critical role in enhancing crop productivity while offering opportunities to reduce nitrous oxide emissions through improved nitrogen use efficiency and targeted nutrient management strategies.

Biologically fixed nitrogen: Nitrous oxide (N_2O) emissions from agricultural systems are impacted by the availability of mineral N as well as the existence of bacteria that fix nitrogen (N). Legume crops like soybeans have a symbiotic relationship with microorganisms that fix nitrogen, including *Rhizobium* sp. Legumes fix ambient N_2 gas during active

Table 1. Effect of organic, inorganic and enhanced efficiency fertilizer induced N_2O emission from fertilized soil

Fertilizer Type	Source	N Release Pattern	Impact on N_2O Emissions	Environmental Effect	Cost
Organic	Natural (e.g., manure, compost, plant residues)	Slow and variable	Can reduce N_2O if matched to crop needs; otherwise may increase due to high C:N ratio (68)	Improves soil health, increases organic matter (69)	Low-Moderate
Synthetic	Industrially manufactured (e.g., urea, ammonium nitrate)	Rapid and short-term	High potential for N_2O emissions if overapplied or poorly timed (70)	May lead to leaching, acidification, pollution (71)	Low
Enhanced-Efficiency Fertilizer (EEFs)	Chemically or physically modified synthetic fertilizers (e.g., slow-release, nitrification inhibitors)	Controlled and prolonged	Significantly lower N_2O emissions by synchronizing N release with crop uptake (72)	Minimizes losses, more environmentally friendly (73)	High

growth and convert it into NH_4^+ ions, which then are used to create protein molecules. A comparison of N_2O emissions from soybean and corn crops within a corn-soybean rotation which results in slightly increase the N_2O emission soybean in two seasons has been investigated (79). Protein components in residues (both above and below ground) undergo degradation following the harvest of legume crops. When NH_4^+ ions are released because of this breakdown, they can be nitrified and denitrified to produce N_2O emissions. This association can be attributed to the soil's greater supply of mineral N (NH_4^+ and NO_3^-) (80).

Mitigation strategies for N_2O emission in agriculture

Agronomic practices

Nitrogen levels: Researchers examined the effects of various nitrogen (N) fertilizers on nitrous oxide (N_2O) emissions in agriculture. They found that the best N rate for increasing grain yields was 101 kg N/ha in maize (81). N_2O emissions climbed dramatically to about 450 g N/ha/day at N rates over 134 kg N/ha and then they somewhat decreased once grain yields were maximized. At 134 kg N/ha, the highest proportion of fertilizer N lost as N_2O was recorded. With an increase in N rates above 134 kg N/ha, the proportion of applied N lost as N_2O gradually decreased to 2-4 %. A reduction in N fertilizer inputs to crop-needs-only levels could lower agricultural N_2O fluxes without appreciably lowering yields. The availability of N in the soil determined how N_2O emissions were distributed (82). The relationship between soil water content and nitrogen availability determined the number of emissions.

Greater allocation of N_2O emission factors occurs when fertilizer applications surpass the ecosystem's capacity to absorb N. To put it another way, using too much fertilizer can increase N_2O emissions. For example, in a particular cropping study (83) observed that when N rates surpassed 80 kg/ha, N_2O emissions rose. Similar to this, in a research on irrigated corn (84), N rates above 100 kg/ha caused a considerable increase in N_2O emissions. The development of effective N_2O emission parameters for estimation was carried out earlier (85). The predicted N_2O emission coefficients in Ontario's agricultural districts varied from 0.0115 to 0.0130 kg N_2O-N per kilogram of applied N. Processes like NH_3 volatilization, leaching and run-off losses result in indirect N_2O emissions (86).

Nitrogen placement: The study shows that the depth of application affected the N_2O emissions from soil fertilized with anhydrous NH_3 (87). N_2O emissions were 107 % higher at 30 cm than they were at 10 and 20 cm depths of injection. Depth had a less noticeable impact on N_2O emissions when 225 kg N ha^{-1} of anhydrous NH_3 was sprayed. It's noteworthy that anhydrous NH_3 may prevent nitrifying bacteria from growing and permit nitrite to accumulate in soil. When soil depth was increased to 30 cm under aerobic circumstances, there was no increase in denitrifier enzyme activity or potential rate of N_2O emission production has been found in the study (88). The N_2O emissions that occurred after maize crops with various tillage practices were treated with 160 kg N ha^{-3} of ammonium nitrate (side-dress) (Minimum Pollution) were examined (88). For a period of three years, the average N_2O emissions from fertilizer buried two centimetres deep was 2.8 kg N_2O-N ha^{-1} $year^{-1}$. (A Rise in Emissions) Zone-tillage emits 3.0 kg N_2O-N ha^{-1} $year^{-1}$, No-tillage emits 3.7 kg N_2O-N ha^{-1} $year^{-1}$ and Mold board plough tillage emits 4.8 kg N_2O-N ha^{-1} $year^{-1}$ at a placement depth of 10 cm (89).

Corn yields increased by 4 % with deeper planting (7.5 t ha^{-1} vs. 7.2 t ha^{-1}) although peak soil NO_3 levels decreased with shallower placement. When optimizing agricultural techniques for production, it is critical to consider the impact they have on greenhouse gas emissions and soil health (90). A large amount of nitrogen (N) fertilizers may be lost to evaporation as ammonia (NH_3) when they are put to the soil's surface and not integrated, particularly in humid areas. NH_3 is not a greenhouse gas (GHG) in and of itself, but the research conducted (91) discovered that the depth of anhydrous NH_3 application affected N_2O emissions. Higher NH_3 loss was caused by shallow placement, which helps to partially explain the reported data. Whether the applied nitrogen is lost as NH_3 or remains available in the soil for plant uptake, it is typically assumed that the amount of N_2O released is the same (92).

Nitrogen timing: Nitrogen fertilizer timing greatly impacts N_2O emissions. Optimizing application schedules reduces emissions while preserving yields. Spring N application cuts N_2O emissions by 50 % versus fall, as seen in an Alberta study, without reducing wheat yields. This aligns N supply with plant uptake, limiting excess nitrate (93). Aligning N application with crop demand is key. An Ontario study found side-dressing at V8 reduced N_2O emissions (0.88 vs. 2.12 kg N ha^{-1} at planting) without lowering yield, ensuring N availability when needed (94). Timing of nitrogen application, such as fall versus spring, can affect nitrate leaching. Fall applications have shown lower nitrate levels compared to spring applications (95). Utilizing split applications allows for adjustments based on crop needs and environmental conditions, which can optimize yield and minimize losses (96). Soil nitrate testing enables N rate adjustments, improving efficiency and cutting N_2O emissions. Aligning N application with crop demand through spring application, side-dressing and in-season adjustments reduces emissions while sustaining yields (97).

Technologies

Urease Inhibitors and enhanced-efficiency sources: Urease inhibitors are recommended for the most effective management of nitrogen (N) to lower greenhouse gas emissions. NH_3 emissions may be reduced by urease inhibitors (98). By inhibiting urease enzymes, these inhibitors reduce losses to the atmosphere by delaying the conversion of urea to NH_3. In circumstances when there is a high possibility of NO_3-N leaching losses and/or N_2O emissions, nitrification inhibitors ought to be employed (99).

Applying slow-release Polymer Coated Urea (PCU) fertilizer, as opposed to urea with or without the nitrification inhibitor DCD, was found (100) to result in decreased initial N_2O emissions. Nonetheless, N_2O emissions persisted for 60-80 days following fertilization, resulting in higher overall emissions from PCU-treated plots than from urea-only plots. When urea-based fertilizers, such as slow-release urea, were used on turfgrass, the amount of N_2O emissions produced was less than when NH_4NO_3 (ammonium nitrate) was found (101). Studies have repeatedly demonstrated that, in comparison to traditional fertilizers (such urea), slow-release or controlled-release fertilizers result in lower emissions of N_2O. These results demonstrate how creative fertilizer formulations can strike a balance between agricultural productivity and environmental sustainability (102).

System level

Tillage: The no-till method offers several advantages by minimizing soil disturbance, which in turn helps reduce erosion. Enhanced agricultural sustainability can maintain soil health and productivity (103). No-tillage lowers greenhouse gas emissions while preserving yield by maintaining soil structure, moisture and N_2O levels. It also increases soil carbon and organic matter (103). Organic matter (OM) promote denitrification and raise emissions of N_2O. When elevated levels of OM, particularly in the form of dissolved organic carbon (DOC), provide a readily available energy source for denitrifying microorganisms. This increased carbon availability stimulates microbial activity, thereby accelerating the denitrification process (104). Nitrate (NO_3^-), through a microbial process known as denitrification, is converted into N_2O and N_2 gasses (105). No-till farming has been shown to lower CH_4 emissions (106). The application of nitrapyrin, a nitrification inhibitor, in conjunction with urea fertilizer has been shown to reduce N_2O emissions by up to 64 % in minimum tillage (MT) and 58 % in conventional tillage (CT) systems (107). Nitrogen Inhibitors (NI)s can enhance NUE by approximately 55 % in MT and 46 % in CT systems, indicating their role in optimizing nitrogen management (107). No-till systems emit less CH_4 than plough tillage, while their impact on N_2O emissions remains debated. Appropriate tillage practices are crucial for managing soil structure, aeration and microbial dynamics, thereby influencing nitrous oxide emissions and contributing to more sustainable and climate-resilient agricultural systems.

Water management: Drought necessitates irrigation, but pumping water emits CO_2 (108). Mulched Drip Irrigation (MDI) conserves water and minimizes emissions (109). Excess water creates anaerobic conditions conductive to denitrification, increase N_2O. Sprinkler irrigation decreased N_2O emissions by 40% over a three-year trial (110). Although early-season drainage might reduce cropping systems' total budget, it may also cause nitrogen loss as N_2O (111). found that drip irrigation reduced N_2O emissions compared to furrow irrigation has found. that continuous flooding in a saline-alkaline paddy field doubled N_2O emissions during the mature stage compared to intermittent flooding has been reported (113). A study observed that, relative to furrow irrigation, mulched drip and drip filtration irrigation lowered N_2O emissions by 16.4 % and 60.9 %, respectively (109).

Water management practices such as Continuous Flooding (CF) results in lower N_2O emissions compared to other practices, with emissions accounting for only 12.10 % of those from normal aeration treatments (114). Controlled Irrigation (CI) leads to higher cumulative N_2O emissions (2.5 kg N ha^{-1}) compared to traditional irrigation (1.0 kg N ha^{-1}), primarily due to soil drying phases (115). Alternative Wetness and Dryness Irrigation (AWDI) while improves water use efficiency, it can increase N_2O emissions by 67 % compared to continuous flooding (116). N_2O emissions peak during specific periods, such as mid-season aeration and shortly after re-flooding, contributing from 70.30 % to 94.26 % of total emissions during the rice-growing season (114). The highest emissions from CI fields occur approximately 8 days after fertilizer application, influenced by soil moisture and temperature conditions (115). Effective water management is essential for regulating soil moisture conditions that influence microbial activity, making it a key strategy for minimizing nitrous oxide emissions and enhancing nitrogen use efficiency in agricultural systems.

Cropping system: Legume crops can be rotated into the agricultural rotation as a substantial way to minimize emissions by reducing reliance on N inputs (117). But it's important to remember that nitrogen from legumes can also increase emissions of nitrous oxide (N_2O) (118). It has been demonstrated that rotating soybeans and corn increases yields and lowers emissions of nitrous oxide (N_2O) (119). Less intensive farming still emits N_2O but shows how better management can cut emissions and mitigate climate change (120). Addition of legume crops to the crop rotation can lower N_2O emissions by encouraging biological N fixing and lowering N use (121). The management of cover crop residues is critical to minimize N_2O emissions in N-fertilized systems (122). Cropping systems not only enhances nitrogen use efficiency but also serves as a pivotal strategy for mitigating nitrous oxide emissions, positioning them as essential tools in climate-smart agricultural practices.

Nutrient sources: Fertilizer imbalance, abuse and overuse in agriculture have long been issues (123). Improving crop nitrogen use reduces excess soil NO_3^- and N_2O emissions. Ammonium sulfate lowers CH_4 more than urea but increases N_2O (124). Nitrification inhibitors reduce N_2O emissions from ammonium sulfate fertilizer, emphasizing responsible use to minimize environmental impact. Fertilizers affect N_2O emissions due to varying NH_4^-, NO_3^- and organic C content. A maize-wheat field in Brazil, urea and slurry increased N_2O emissions by 33% and 46%, with emission factors of 0.27% and 0.76% has been studied (125). A 13 years of nitrogen fertilization in northeast China's temperate grassland altered soil properties, significantly increasing cumulative N_2O emissions has been observed (126). The choice and management of nutrient sources whether organic, inorganic, or enhanced-efficiency are pivotal in controlling nitrogen availability and microbial transformations, thus playing a vital role in mitigating nitrous oxide emissions from agricultural soils.

Optimizing nitrogen application: Efficient nitrogen application reduces N_2O emissions while preserving yields. Research shows application rate and management greatly impact emissions. Higher N fertilizer application rates are associated with increased N_2O emissions (127). Improving nitrogen (N) utilization efficiency is crucial for reducing N_2O emissions; however, its effectiveness can vary due to a range of influencing factors (128). Yield-scaled N_2O emissions offer a quantitative measurement. Optimizing N fertilizer use efficiency produces the lowest yield-scaled N_2O emissions

(129). This method is preferable to just reducing N application rates. The lowest yield-scaled N_2O emissions occur at N rates between 180 and 190 kg N ha^{-1} emissions may skyrocket at this level. A meta-analysis discovered that optimizing fertilizer application lowered N_2O emissions by an average of 31 % (130). This method not only reduces N_2O emissions, but it also helps to reduce other environmental pollutants like water pollution and ammonia volatilization. Applying optimal N and P fertilizers boosts yield and lowers GHG emissions. N_2O emissions depend on fertilizer type, rate and timing (131). Maintaining nitrogen at agronomically optimal yet non-excessive levels reduces N_2O risks (132). Optimizing nitrogen application in terms of rate, timing and placement is essential for maximizing crop uptake, minimizing nitrogen losses and effectively reducing nitrous oxide emissions in agricultural systems.

Enhanced-efficiency fertilizers: High-efficiency fertilizers include nitrification and urease inhibitors, as well as polymer-coated fertilizers. Nitrification inhibitors (Dicyandiamide (DCD), nitrapyrin) reduce ammonia oxidation by inhibiting nitrifier activity (133). Polymer-coated fertilizers release nitrogen (N) more slowly than ordinary fertilizers. Nitrification inhibitors and polymer-coated fertilizers have been shown to reduce N_2O emissions in Andosol and Fluvisol soil (134). Studies conducted around the world have found that enhanced-efficiency fertilizers have variable degrees of success in reducing N_2O emissions. Differences in efficacy may be caused by environmental conditions and agricultural techniques unique to each region. A meta-analysis by a study (135) reported average N_2O emission reduction of 38 % for nitrification inhibitors and 35 % for polymer-coated fertilizer. Polymer-coated fertilizers mean reduction of 35 %. Urease inhibitors did not significantly reduce N_2O emissions (136). In comparison to traditional fertilizer (2.7 mg/m^2/day), soil fertilized with nano fertilizer N (NH_4^+ form) and zeolite (carrier) showed reduced N_2O emission (1.8 mg/m^2/day) (137). In soil treated with NO_3 form of N, CH_4 emissions were 34.8 mg/m^2/ day. compared to 36.8 mg/m^2/day of conventional fertilizer (138). Enhanced-efficiency fertilizers offer a promising strategy for synchronizing nitrogen release with crop demand, thereby improving nitrogen use efficiency and significantly reducing nitrous oxide emissions from agricultural soils.

Conclusion

Reducing nitrous oxide emissions from agriculture is no longer a choice it's a necessity in the face of accelerating climate change. This review underscores a clear message integrated nitrogen management is the cornerstone of climate-resilient agriculture. Rather than relying on isolated practices, blending optimized fertilizer use, water and tillage strategies and enhanced-efficiency products offers a synergistic path to both productivity and sustainability. However, key questions remain. How do these strategies interact under diverse field conditions? Can long-term effects be reliably captured and predicted? Addressing these research gaps is vital. Moving forward, farmers must be empowered to adopt tailored, site-specific nitrogen practices that align with crop needs and environmental thresholds. Policymakers should incentivize innovation supporting both research and the practical implementation of low-emission technologies. Ultimately, bridging science and practice through integrated nitrogen management is not just a technical solution it's a strategic imperative for feeding the world without heating it.

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Authors' contributions

MW has done sample collection, analysis, compiling and drafting the manuscript; SB was involved in conceptualization, guidance and reviewing the manuscript. SM was involved in guidance and reviewing. PK involved in correcting the paper PC was involved in data analysis.

Compliance with ethical standards

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