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Nitrogen and Nitrate Dynamics in Cropping Systems: A Review Toward Sustainable Nutrient Management

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ABSTRACT

The intensification of agriculture has led to a significant rise in nitrogen (N) fertilizer use to meet global demands for food, bioenergy, and fiber. Nitrogen is essential for plant growth and is mainly absorbed as nitrate (NO_3^-), ammonium (NH_4^+), and nitrite (NO_2^-). However, conventional nitrogen application practices are often inefficient, resulting in nitrate leaching, greenhouse gas emissions, and long-term environmental degradation. Nitrate leaching can increase by up to 50% under poorly managed nitrogen regimes, particularly in winter wheat systems. This review critically synthesizes the agronomic role of nitrogen in plant nutrition, the biochemical pathways of nitrification and nitrate leaching, methods for tracking soil nitrogen transformations and microbial processes involved in gaseous nitrogen losses. Special attention is given to nitrous oxide (N_2O), a greenhouse gas with a 100-year global warming potential 273 times that of carbon dioxide (CO_2). Sustainable practices such as optimized nitrogen scheduling, precision agriculture, and diversified crop rotations can reduce losses without compromising yields, although reported effects vary with crop, soil, climate and management context. The main conclusion is that sustainable nitrogen management must evaluate nitrate leaching, ammonia volatilization and N_2O emissions together rather than as isolated loss pathways. This review aims to provide a critical synthesis of nitrogen dynamics and to identify practical priorities that improve nitrogen use efficiency (NUE) while minimizing ecological harm.

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Greenhouse gas emissions; nitrate leaching; nitrogen management; nitrogen use efficiency; sustainable agriculture

Introduction

Increasing worries about protecting the environment and the need to feed the world's rising population have made the growing importance of sustainable agriculture. Practices like conservation tillage, use of cover crops, and crop rotation change – especially by combining winter legumes with grains – are key components of the move to more environmentally friendly systems. To enhance soil health and long-term agricultural flexibility, these strategies seek to improve nutrient cycling, increase biodiversity, and increase soil cover. One of the most important macronutrients for plants is nitrogen (N), which is given as fertilizer to produce crops with high quality and yields. The main forms of nitrogen that plants absorb are nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). The amounts of these substances in plant tissues show the efficiency of uptake as well as the kinetics of internal absorption. Thus, a plant's nitrate and nitrite concentrations are physiological indicators of its nitrogen case and capacity to keep a constant nitrogen economy. Although its importance in agronomy, excessive nitrogen using can be one of the most damaging nutrients to the environment. traditional fertilization

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usually produces suboptimal nitrogen use efficiency (NUE) because of the nitrogen loss from volatilization, leaching, and denitrification. These losses lead to a lot of environmental problems, such as eutrophication, groundwater pollution, and the emission of greenhouse gases like nitrous oxide (N_2O). Also, the increase of residual nitrogen in the soil poses a long -term danger that may persist beyond a single cropping season, affecting the quality of the environment and production. The present condition of research on nitrogen action in agricultural systems is thoroughly summarized in this review. It focuses on four main topics: the basic role of nitrogen and nitrate in fertilization and plant growth; the techniques and effects of nitrate leaching and nitrification during winter wheat production; research methods to evaluate soil nitrogen transformations; and the emission of nitrogen gases from earth, especially N_2O. With this framework, the review aims to support the development of sustainable nutrient management practices that increase agricultural yields while reducing environmental damage.

This study is a critical synthesis rather than a quantitative meta-analysis, as the literature was compared based on nitrogen loss pathways, crop-context, measurement methods, and management practices. The synthesis is therefore not limited to a list of published results, but highlights contradictions among the studies, context-dependent responses, and research priorities for future nutrient management research.

Overview of nitrogen management in agricultural systems

Importance of nitrogen and nitrate in plant nutrition and fertilization strategies

A central part of modern agriculture is fertilization, which provides the necessary nutrients for the greatest possible plant yield and growth. Plants' physiological processes depend on the availability and absorption of a variety of mineral elements, which are mostly taken up from the soil by the roots and then moved to specific organs to support vital structural and biochemical activities (Paez-Garcia et al. 2015). Specialized transporters found in the plasma membranes of root cells and root hairs facilitate this nutrient absorption (Kimura et al. 2019). Environmental factors, agronomic methods, and soil structure all have an effect on this process (Singh et al. 2023).

Based on their necessary quantities, the 17 substantial elements needed by plants are splitting into macronutrients and micronutrients. Nitrogen (N), phosphorus, potassium, calcium, magnesium, sulfur, carbon, hydrogen, and oxygen are examples of macronutrients that must be present in amounts greater than 1000 mg per kilogram of plant dry weight. On the other hand, less of the micronutrients are needed, including iron, zinc, manganese, copper, boron, molybdenum, chlorine, and nickel (Sinha and Tandon 2020). Among these, nitrogen is especially noticeable due to its primary function in enzymatic processes, protein synthesis, and photosynthesis (Leghari et al. 2016).

Nitrogen in soil exists in several chemical forms as part of the dynamic nitrogen cycle, yet only nitrate (NO_3^-) and ammonium (NH_4^+) are readily absorbed by plants. Nitrate, being highly mobile, is particularly significant during active growth stages, where it supports protein formation and biomass accumulation (Mai et al. 2024). However, nitrogen imbalance – either deficiency or excess – can result in agronomic and environmental issues. Deficiency limits crop yields, while excess nitrogen promotes leaching of mobile nitrate and nitrite into groundwater and surface water, especially under irrigation or rainfall events (Bray 1945). Nitrate and nitrite ions are widely present in natural systems, including soils, water bodies, and certain food products, making their monitoring essential for plant health and environmental safety (Hassan 1972).

The intensification of global agriculture has dramatically increased cereal yields – by 3.4 times between 1961 and 2020 – driven primarily by a 9.5-fold rise in nitrogen fertilizer application (FAO 2020; Yokamo et al. 2022). Yet, nitrogen use efficiency (NUE) remains low. Less than 50% of the annually applied 107.6 million tons of nitrogen fertilizers is absorbed by crops, while the remainder is lost to the environment or retained in the soil profile (Lassaletta et al. 2014). This unused nitrogen, amounting to 55 Tg of reactive N per year, contributes significantly to air and water pollution, soil degradation, and poses risks to human health (Eickhout et al. 2006; Erisman et al. 2013). Predictions estimate that nitrogen pollution could rise by 150% by 2050, with agriculture contributing 60% of this burden (Bodirsky et al. 2014; FAO 2020). In response, numerous global initiatives have been launched to enhance NUE and curb nitrogen losses (Mirkhani et al. 2023; Zhu et al. 2023; Park et al. 2024).

Once nitrogen fertilizer is applied to the soil, it follows one of three main pathways: uptake by crops, loss to the environment, or retention in the soil as residual nitrogen. A meta-analysis covering wheat, maize, and rice cropping systems found that nitrogen recovery ranged from only 34% to 45%, indicating significant inefficiencies (Yu et al. 2022). Annually, 15–20% of applied nitrogen accumulates in the soil, forming a residual pool (Sebilo et al. 2013; Van Meter et al. 2016). Long-term field studies using^{15} N-labeled fertilizers have shown that up to one-third of nitrogen applied in cereal systems remains in the soil post-harvest (Quan et al. 2021; Lei et al. 2024). This residual nitrogen can benefit subsequent crops by reducing fertilizer requirements, but it also increases the risk of nitrate leaching, greenhouse gas emissions, and prolonged water pollution – especially due to nitrogen legacies from decades of intensive fertilization (Van Meter et al. 2018; Ascott et al. 2021; Basu et al. 2022).

Despite its agronomic and environmental importance, residual nitrogen is often overlooked in fertilizer recommendation systems. Studies from various agroecosystems have shown that when residual NO_3^- -N in the upper soil profile exceeds certain thresholds—20–30 mg/kg in the 0–30 cm layer in the U.S. (Blackmer et al. 1989; Binford et al. 1992). 100 mg/kg in South Carolina (Raza and Farmaha 2022), or 200 kg N/ha in the 0–90 cm layer in the North China Plain (Cui et al. 2008) – additional nitrogen application does not improve yields and may even be detrimental. They demonstrated that nitrogen availability above 87 kg/ha is sufficient for optimal maize performance without the need for extra fertilization.

Conventional NUE metrics frequently disregard the contribution of residual nitrogen, assuming all nitrogen uptake is derived from current-season fertilization. This misrepresentation can result in overfertilization and misinformed nutrient planning, especially in systems with a history of huge nitrogen inputs (Thorup-Kristensen et al. 2020; Lei et al. 2025). Therefore, developing accurate and integrative NUE indicators that account for residual nitrogen strategies is essential for improving fertilizer efficiency, decreasing environmental risks, and promoting sustainable nutrient management.

Overall, these studies show that nitrogen use efficiency cannot be determined solely on the basis of fertilizer uptake observed during the crop season in question. While nitrogen residues in the soil may benefit subsequent crops, they can also mask the environmental costs of additional fertilization. Future recommendations must therefore take into account the amount of nitrate remaining in the soil, the nitrogen requirements of crops, and the risk of leaching off-season, rather than viewing individual growing seasons in isolation from each other. To clarify the critical summary, Table 1 summarizes the

Table 1. Critical comparison of nitrogen-loss pathways.

Nitrogen pathway or issue	Main drivers emphasized in the literature	Critical interpretation for nutrient management
Residual soil nitrogen	Repeated fertilizer inputs, low crop recovery, soil organic matter mineralization and legacy nitrogen pools.	Residual nitrogen can reduce fertilizer demand in the following crop, but it also increases leaching and emission risk if it is ignored in recommendations.
Nitrate leaching	Mobile nitrate, rainfall or irrigation, drainage, shallow rooting, high autumn or off-season nitrate supply and mismatched fertilizer timing.	Leaching control is highly site-dependent; the same practice may perform differently under contrasting soil texture, rainfall and rooting conditions.
Ammonia volatilization	Surface-applied urea or manure, high pH, warm and windy conditions and delayed incorporation.	Measures that reduce volatilization may improve nitrogen retention, but retained nitrogen must still be managed to avoid later leaching or N_2O emissions.
Nitrous oxide emissions	Nitrification and denitrification under high mineral nitrogen, available carbon, wet or poorly aerated microsites.	N_2O mitigation should be evaluated together with nitrate leaching because practices that reduce one pathway may shift losses to another pathway.

most important pathways of nitrogen loss, their agronomic driving factors, environmental impacts, potential mitigation strategies, and current gaps in research.

Nitrate leaching and soil nitrification under winter wheat cultivation

One of the most extensively grown and used grain crops in the world, wheat (Triticum aestivum L.) is a main food for billions of people. Because of its versatility in a wide range of climates, it is substantial to the world's food security. However, issues including increased competition for natural resources, shifting climatic conditions, and rapid population growth are posing an increasingly significant challenge to the sustainability of wheat production. These difficulties highlight the pressing need for environmentally friendly and productive sustainable farming methods (Amo et al. 2022).

Nitrogen (N) is the most important and limiting nutrient for crop development among all plant nutrients. In order to achieve the required yields and grain quality, winter wheat, an extensively cultivated crop that is substantial to human and animal nutrition, needs large nitrogen inputs. However, because of its high mobility in soils, nitrogen causes significant losses by volatilization, leaching, or denitrification, especially when applied in excess (Antošovský et al. 2024). Given the huge pressure to meet the world's expanding food demands, nitrogen fertilizers account for more than 50% of all fertilizer use worldwide (Wang X et al. 2021).

Nitrogen fertilizer has been shown in many studies to improve wheat yield and grain quality (Chen et al. 2008; Mohammed et al. 2013). Even so, because of its environmental mobility, nitrogen loss from agricultural soils can amount to as much as 70% (Tian et al. 2020). Nitrogen utilization efficiency (NUE) in the field usually falls between 32% and 53% (Zhang et al. 2015; Dawar et al. 2021), but it can rise to 50–70% if nitrogen is provided at the moment when the crop needs it most (Wiesler 1998). Weather, fertilizer type and placement, application time, and soil combination all have a big effect on how much nitrogen is lost (Santillano-Cázares et al. 2018).

The effects of low NUE extend beyond agronomic inefficiency. Significant environmental problems, decreased soil productivity, and financial losses result from it. Nitrate (NO_3^-) leaching, ammonia (NH_3) volatilization, and other nitrogenous gas emissions are the main causes of air and water pollution, which can be harmful to both human and animal health (Cameron et al. 2013; Wu et al. 2017; He et al. 2018). In addition, by causing eutrophication, contributing to groundwater nitrate contamination, and degrading air quality through ozone production, these emissions worsen climate change (Ravishankara et al. 2009; Umar et al. 2020). Enhancing NUE is therefore a top priority for sustainable agriculture as well as an agronomic need.

According to estimates, food production must increase by 70–100% in order to feed the world's expected 9 billion people by 2050 (Godfray et al. 2010). This scenario may require a doubling of global nitrogen application rates (Subbarao et al. 2012) and suggests a huge reliance on synthetic nitrogen fertilizers, mostly made via the Haber–Bosch process (Coskun et al. 2017). However, this intensification would cause expansive nitrogen losses, estimated at 6.15×10^7 tons per year (Schlesinger 2009), which would have a negative effect on the ecosystem. The European Union has set the legally binding objective of climate neutrality by 2050 and a net greenhouse gas emission reduction target of at least 55% by 2030 compared with 1990 levels (Regulation (EU) 2021/1119). In addition, Directive (EU) 2016/2284 addresses the reduction of national emissions of certain atmospheric pollutants, including ammonia (Ray et al. 2021).

Economic and environmental incentives, as well as the continuous rise in fertilizer prices, have made it even more imperative to improve NUE and put plans in place to reduce reactive nitrogen loss (Duff et al. 2022). According to Chen et al. (2014), a major contributor to nitrogen inefficiency is incorrect nitrogen application techniques, which can result in up to 50% of applied nitrogen being lost through nitrous oxide (N_2O) emissions, nitrate leaching, and ammonia volatilization (Lynch 2019; Yan et al. 2021). These losses limit the possible yield improvements (Cossani et al. 2012) and decrease the amount of nitrogen available for wheat uptake (Omonode et al. 2017; Wang Y et al. 2019). As a result, in order to sustainably satisfy the world's food demands, nitrogen fertilization procedures must be optimized to minimize environmental impacts, support wheat's absorption of nitrogen, and improve overall NUE.

Research approaches to measuring nitrate leaching, nitrification, and soil nitrogen under agricultural practices

The results for crop productivity and environmental sustainability continue to create a lot of interest in the expanding global use of chemical fertilizers. The Food and Agriculture Organization (FAO 2020) reports that the world consumed 37,042 units of potash, 45,275 units of phosphorus, and 118,763 units of nitrogen in fertilizer in 2020. Expectations indicate that the total amount of fertilizer used worldwide will increase even further, from 177.2 million metric tons during the 2011–2012 growing season to 191.8 million metric tons in 2022–2023, or an approximate 8.24% increase over 11 years. However, many environmental organizations and scientists consider these levels extravagant because of the effects they have created, such as nutrient runoff, eutrophication of aquatic systems, and increased greenhouse gas emissions that have led to global warming.

Researchers and agricultural professionals now have strong tools to evaluate plant-soil-environment interactions thanks to developments in spatial and temporal monitoring. More careful estimates of crop growth and climatic conditions have been made possible by the integration of spatiotemporal data, which are collected via technologies including satellite images, remote sensing platforms, automated weather stations, and in-situ soil and crop sensors. The identification of correlations supporting the development of genetically improved crop varieties has been made easier by the analysis of such data, which include soil composition, moisture dynamics, temperature changes, and meteorological direction. These correlations have the potential to transform modern agricultural systems (Mulla 2013; Liu et al. 2017; Shen et al. 2019; Wang Y et al. 2019).

Soil analysis remains central to agronomic planning and environmental stewardship. Traditional methods, predominantly based on wet chemical analysis, are labor-intensive, costly, and rely heavily on hazardous reagents. For example, it is estimated that 1.5 billion hectares worldwide are allocated to agriculture. If two samples per 5 hectares (across two soil depths) were collected, approximately 600 million soil samples would be required for chemical and granulometric testing. The analysis of organic matter (OM) alone using wet oxidation techniques would consume around 840,000 kg of dichromate and ammonium ferrous sulfate, along with 3 million liters of sulfuric acid – posing considerable risks if improperly disposed of. Consequently, environmentally benign alternatives such as proximal sensing have been proposed as viable solutions for large-scale, low-impact soil diagnostics (Demattê et al. 2019).

Nevertheless, conventional soil analysis is susceptible to various sources of uncertainty, including sampling inconsistencies, analytical technique limitations, reagent quality, equipment variability, and operator influence (Olsen and Sommers 1982). Numerous techniques have been developed for the detection of nitrate and nitrite ions, ranging from polarography, voltammetry, and fluorimetry to more advanced systems such as flow injection analysis, bioamperometry, gas chromatography-mass spectrometry, and kinetic assays. However, these methods often involve complex procedures or require sophisticated and expensive instrumentation, making them impractical for routine field applications (Gauthama et al. 2020).

Added complexity comes from differences in procedures. O'rourke and Holden (2011) pointed out that already the generic analysis of the soil is influenced by the purity of the reagents, the calibration of the equipment depending on the brand used, and the repetition of procedural steps themselves – a number of reasons for reaching different outcomes even when analyzing the same sample. Similarly, Cantarella et al. (2016) found that significant discrepancies existed in soil testing results, both within the same laboratory (in one case) and among different organizations. These findings have aroused a growing interest in research for alternative soil diagnosis methodologies that are not only fast and inexpensive but also environmentally friendly and reliable under applicable conditions (Demattê et al. 2019).

In this regard, new real-time monitoring technologies capable of tracking soil ammonia emissions day and night, over a series of meteorological conditions, have been developed. They have the advantage of high time resolution with low maintenance needs. The obtained data can yield important information on the dynamics of nitrogen transformation and consequently, provide assistance for designing better fertilization strategies and controlling ammonia volatilization to the atmosphere (Zhou et al. 2021). According to Peng et al. (2010), the morphological attributes and placement of crop roots play critical roles in nutrient acquisition efficiency and are strongly regulated by the soil nutrient environment (Rogers and Benfey 2015; Guo et al. 2019). Root systems in the upper 0–60 cm of the soil profile are particularly important for N uptake, controlling the growth of the aboveground biomass, and ultimately the formation of grain yield (Peng et al. 2010). Furthermore, deep roots have been observed to contribute positively to the uptake of subsoil water and nitrogen resources (Wiesler and Horst 1994).

In semi-wet zones, manure is generally applied on the surface only by traditional methods of fertilizer application. Such practices are likely to cause spatial decoupling of the nutrient supply zones and the natural root distribution, and also to retain fertilization-derived nutrients in the upper layer (Wu et al. 2022). Under such conditions, one solution to reconcile this mismatch is to manage fertilization in such a way that nutrients are strategically placed in root-active zones and are targeted to the plant rather than soil (i.e., "feeding the roots, not the soil"), which has been suggested as a potential strategy to enhance both water and N use efficiencies of cropping systems. Deep application of N fertilizers has been found to be of considerable benefit for improving nutrient use efficiency and crop productivity (Nkebiwe et al. 2016). By coordinating the timing and duration of nitrogen release with root growth rhythms, this approach also provides a better-targeted nutrient supply in accordance to the spatial and temporal patterns of root growth (Cheng et al. 2020; Lu et al. 2021).

However, the optimal depth for deep placement of fertilizer, and its agronomic effect, can vary greatly depending on site-related factors, including soil type distribution, climatic situation, and genotype of the crop. Modifying depth of fertilizer application changes the spatial location of nitrate nitrogen (NO_3^- -N) in the soil profile and thus root system spatial orientation and architecture. In addition, the vertical transportation and bioavailability of deep N are also affected by rainfall patterns and hydrological movements (Zhou et al. 2016). As a result, the plant root morphological response to the enhanced inorganic soil N availability arising from changes in fertilization depth strongly varies with soil moisture status (Ke et al. 2018). Wang et al. studied the application of deep-placed urea under different precipitation conditions on N absorption and root growth in wheat. They found that a suitable depth of urea application indirectly affected wheat nitrogen nutritional status by regulating the spatial distribution of soil nitrate-nitrogen (NO_3^- -N) and enhancing root growth in deeper layers.

This adjustment facilitated more efficient water and nitrogen utilization, especially under dry and normal rainfall conditions, ultimately leading to increased crop yields and maintaining low levels of residual soil nitrate. The study highlighted a strong positive correlation between deep root traits and nitrogen uptake, as shown in (Figure 1), which was key to the observed improvements in nitrogen use efficiency and overall wheat productivity (Wang et al. 2022).

One of the main causes of nitrogen (N) loss in agricultural soils is nitrate leaching which has become a major issue in conventional farming systems. This problem has been made worse by the overuse of nitrogen fertilizers in heavily maintained croplands, making nitrate leaching the primary source of nitrate pollution of groundwater in the area. In many high-input farming places around the world, this phenomenon has become an important ecological, agricultural, and environmental problem (Wang et al. 2017). Many factors, including agricultural management methods (especially fertilizer application rates and practices, irrigation techniques), environmental factors like rainfall, and substantial soil properties like texture and drainage capacity, are closely related to the extent of nitrate leaching (Wang et al. 2006).

Li et al. (2020) conducted a study in the North China Plain that shed light on the ways in which different farming techniques affect soil nitrate leaching. The study offered that nitrogen application rates, irrigation schedules, and rainfall methods all had an essential impact on nitrate leaching in

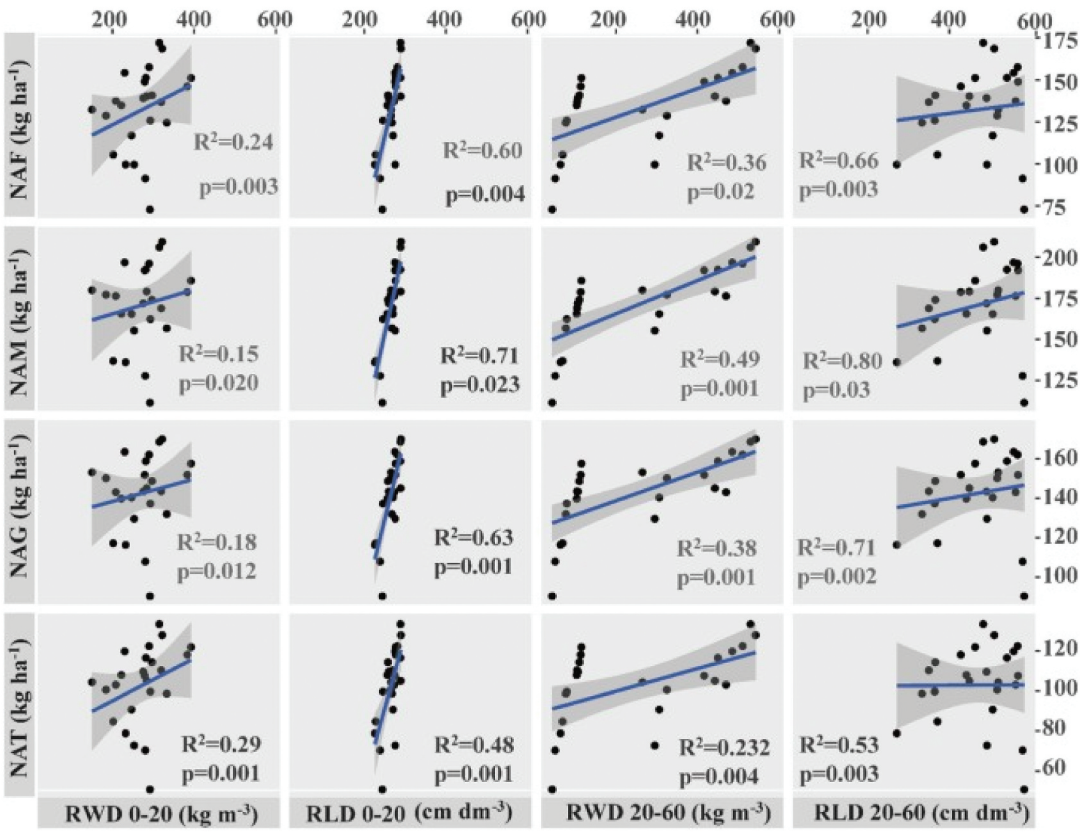

Figure 1. Correlation coefficients for winter wheat's grain N content, N translocation, and root features and plant N accumulation at anthesis and maturity. Notes: RWD 0–20: root weight density in soil layer 0–20 cm; RWD 20–60: root weight density in the soil layer 20–60 cm; RLD 0–20: root length density in soil layer 0–20 cm; RLD 20–60: root length density in the soil layer 20–60 cm; NAG: grain N content; NAT: N translocation; NAF: plant N accumulation at anthesis; and NAM: plant N accumulation at maturity (Wang et al. 2022).

croplands grown in a winter wheat–summer maize rotation system. Nitrogen was provided at up to 600 kg N ha^{-1} in some areas, which led to increased nitrification activity and significant nitrate leaching into the groundwater and the soil. The study used the NLEAP-GIS model and found that leaching potential is controlled by the soil nitrate concentration, which is mostly determined by fertilizer input, in addition to irrigation time and rainfall. In order to balance increasing production with decreasing environmental problems, the authors suggested applying reasonable nitrogen rates, ranging from 100 to 200 kg N ha^{-1} per crop season. Moreover, it was discovered that improving irrigation efficiency was necessary for reducing nitrate leaching and saving groundwater supplies (Li et al. 2020).

Tillage practices also have complex and sometimes contrasting influences on NO_3^- - N leaching (Addiscott and Dexter 1994; Strudley et al. 2008). For example, when compared to conventional plow tillage, no-tillage systems tend to:

(1) According to Isensee et al. (1990), enhance soil hydraulic conductivity by preserving natural preferential flow channels formed by roots and earthworms (Benjamin 1993; Azooz and Arshad 2001; Palmer et al. 2011);
(2) Franzluebbers et al. (1994) claim that soil organic nitrogen content increases due to minimized decomposition, as reduced soil disturbance helps stabilize organic matter within soil aggregates (West and Post 2002; Wright and Hons 2005; Dolan et al. 2006; Zibilske and Bradford 2007);

(3) Slow down residue decomposition since crop residues remain on the surface, where decomposition is slower than when incorporated into the soil matrix (Douglas et al. 1980; Cogle et al. 1987; Coppens et al. 2006; Álvarez et al. 2008);
(4) Enhance soil moisture retention (Blevins et al. 1971).

Collectively, these effects indicate that tillage influences multiple soil processes relevant to nitrate mobility. Particularly, when tillage is conducted shortly before a season of high precipitation and recharging water, the risk of nitrate leaching can be significantly amplified, as demonstrated in (Figure 2).

The influence of tillage on nitrate-nitrogen (NO_3^- -N) leaching is not isolated but rather interacts intricately with a combination of soil properties, climatic variables, and nitrogen (N) management strategies. For instance, the timing and intensity of precipitation relative to tillage operations significantly affect both the overall volume of water percolation and the proportion occurring through preferential flow channels-two critical drivers of nitrate movement through the soil profile. Similarly, the spatial and temporal distribution of nitrogen fertilizer applications directly influences nitrate leaching by altering the size of the NO_3^- -N reservoir in the soil and modulating its partitioning between fast and slow drainage pathways.

Because these interactions are dynamic, previous evaluations have found that tillage's impacts on NO_3^- -N leaching are very varied and context-specific (Addiscott and Dexter 1994; Strudley et al. 2008). In order to properly evaluate nitrate leaching under different tillage systems, post-tillage weather conditions and crop residue management, and nitrogen fertilizer methods, it is essential to consider these factors , especially in wet regions and winter wheat farming. In this regard, lysimeters are effective research instruments that provide direct and comprehensive assessments of the combined effects of environmental factors, hydrological transport, soil nitrogen dynamics, and tillage (Meisinger et al. 2015).

An clear clarification of how tillage affects nitrate leaching may be found in a field experiment carried out by Meisinger et al. (2015) in the Northern Atlantic Coastal Plain of the United States. In

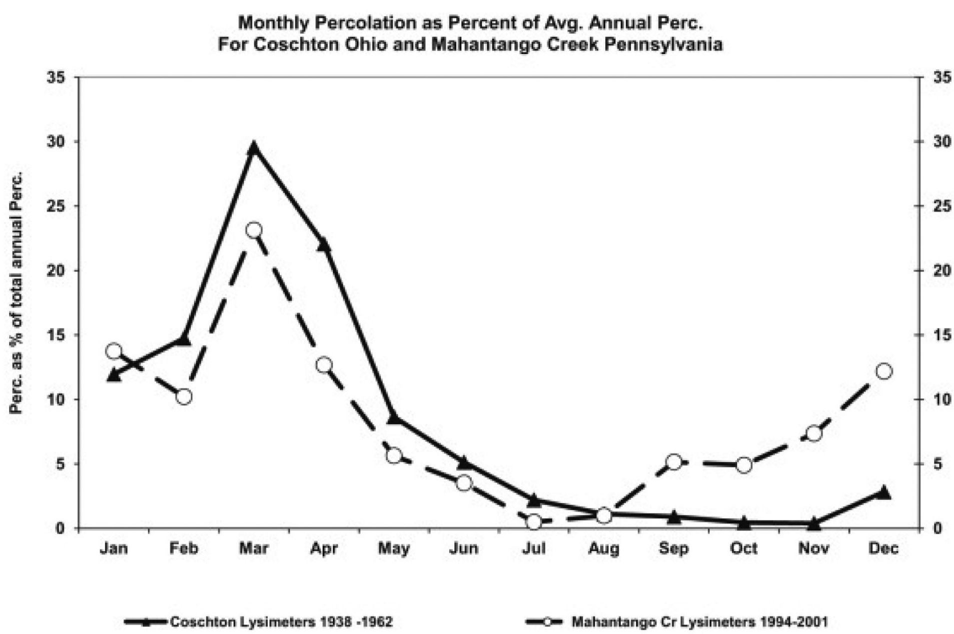

Figure 2. According to Meisinger et al. (2015) shows monthly percolation as a percentage of annual percolation from long-term large-monolith lysimeter experiments at Mahantango Creek, Pennsylvania (open symbols) and Coshocton, Ohio (solid symbols).

order to test the effects of plow tillage (PT) and no-tillage (NT) techniques in winter wheat fields, the four-year study used undisturbed soil lysimeters. The results showed that throughout the autumn establishing phase (mid-October to mid-December), NT methods produced slightly higher volumes of water drainage especially after periods of heavy rainfall. A higher chance of nitrate seeping into the soil and maybe the groundwater was related with this increase in drainage. On the other hand under similar situations, plots under PT offered less drainage and nitrate losses. In light of these results, the authors suggested that spring split treatments be used in NT systems rather than essential nitrogen application in the autumn. In determining nitrate leaching under different tillage regimes, the study highlighted the crucial roles of rainfall timing and strength, fertilizer application schedules, and initial soil moisture status (Meisinger et al. 2015).

A long-term study by Dai et al. (2016) on the Chinese Loess Plateau between 1984 and 2011 tested the effect of nitrogen application rates on winter wheat output and summer nitrate leaching, further highlighting the significance of nitrogen management. Four levels of nitrogen input (0, 90, 150, and 210 kg N ha^{-1}) were investigated over the 27-year experiment, which also tracked nitrate leaching and buildup over a soil depth profile of 0–200 cm. Every year following harvest soil samples were taken at stratified intervals (0–20, 20–40, 40–60 cm, etc.), air-dried, sieved, and their NO_3^- -N concentrations measured. Nitrate was quantified using spectrophotometric methods based on absorbance measurements at certain wavelengths and chemical extraction was executed using 2 M potassium chloride (KCl). This technology made it possible to exactly define the amounts of nitrate at various depths and evaluate their vertical distribution over time. According to the results nitrogen treatments increased grain yield up to 150 kg N ha^{-1}; after that no discernible production increase was seen. Nitrate leaching, however, significantly increased at 210 kg N ha^{-1}, resulting in a significant buildup of residual NO_3^- -N in deeper soil layers. The study concluded that the optimal fertilization rate in this area was 150 kg N ha^{-1}, striking a balance between environmental protection and agronomic productivity (Dai et al. 2016).

As described by Yin et al. (2020), four main access methods have been offered to value nitrogen mineralization: (i) laboratory incubation techniques, (ii) isotopic tracing using ^{15}N-labeled organic remains, (iii) in situ nitrogen balance approaches like the N-difference method, and (iv) process-based simulation modeling. Despite the fact that nitrogen mineralization and immobilization are substantial, yet highly dynamic, processes in soil systems, they are crucial to nitrogen cycling and availability (Nykänen et al. 2009).

However, the first two approaches are heavily constrained by their sensitivity to carefully adjusted laboratory settings, which may not fully explain dynamics at the field scale and may jeopardize the findings' generalizability (Cabrera and Kissel 1988; Johnson et al. 1999). On the other hand, in situ nitrogen balance methods provide more field-representative evaluations; nonetheless, they may introduce confounding variables, especially when fertilization treatments change the nitrogen or water absorption patterns of plants (Cassman et al. 2002). To simulate nitrogen transformation paths over time, process-based samples – like those covered by Yin et al. (2020) – have become very effective tools that can include complicated relationships between weather, soil characteristics, crop growth, and management methods. These models are useful for valuing the long-term effects of fertilization on soil nitrogen stores and nitrate leaching potential when properly examined (Kersebaum et al. 2007).

The use of these models is not without limitation, though. Parameter sensitivity, structural complications , and the tuning of crop measurements, soil properties, and meteorological variables are some of the factors that limit their forecast precision. In addition, these models demand to account for interannual variability and carry-over effects when used for long-term scenarios in order to maintain predicted reliability and consistency (Beaudoin et al. 2008). Consequently, trustworthy model validation and long-term interpretation evaluation be based on the availability and use of long-term, high-resolution datasets.

The work of Svensson et al. (2025), which tested nitrate leaching and nitrogen cycling over a 35-year period in spring grain cropping systems in southern Sweden, provides a noticeable clarification of such long-term modeling. The CoupModel was used in the study to model nitrogen dynamics in both fertilized and unfertilized conditions. Sandy loam soils with subsurface tile drainage were used for the field tests, allowing for constant monitoring of nitrate transport and water drainage. Using a combination of extortion sampling and flow-proportional composite sampling, nitrate concentrations (NO_3^- -N) in drainage water were specified. Colorimetric analysis was then performed in compliance with established European standard techniques. To ensure exact and depth-resolved measurement of soil nitrate concentrations, regular soil sampling was carried out at different depths (usually down to 90 cm). Nitrate was extracted using 1 M potassium chloride (KCl) and quantified using a constant flow analyzer like the Auto Analyzer.

To enhance simulation accuracy, the CoupModel was calibrated through Monte Carlo simulations incorporating over 10,000 parameter combinations, enabling robust capture of the interactions among crop growth, climatic variability, and soil processes. The results demonstrated that annual nitrate leaching in fertilized plots reached 3.7 g NO_3^- -N m^{-2}, more than double the 1.8 g NO_3^- -N m^{-2} observed in unfertilized plots. However, when normalized by crop yield, unfertilized systems exhibited relatively higher nitrate losses due to lower biomass productivity. The study underscored the long-term effects of nitrogen fertilization on both nitrate leaching and soil nitrogen mineralization, and emphasized the necessity of crop-specific model calibration to enhance the accuracy of nitrogen loss estimations (Svensson et al. 2025).

The literature on nitrate leaching is not consistent overall. Reduced tillage, deep soil injection, multiple fertilizer applications, and model-based recommendations can reduce losses under certain conditions, but their effectiveness depends significantly on soil properties, drainage, precipitation amounts, and the depth of crop root systems and the scheduling of nitrogen fertilizer applications. This circumstance-dependence explains why management guidelines must be determined on a site-specific basis, rather than generalized based on a specific plant species, soil type, or climate region.

Nitrogen gas emissions and N_2O fluxes from soil to atmosphere

A potent greenhouse gas with a long atmospheric lifetime, nitrous oxide (N_2O) contributes to both global warming and ozone layer thinning. At 332 parts per billion (ppb) in 2019, its atmospheric concentration has risen by about 23% since 1750 (Ravishankara et al. 2009; “Summary for Policymakers,” 2023).

According to Prather et al. (2015), it is a long-lived and climatically significant gas that can remain in the atmosphere for up to 116 years. According to Tian et al. (2019), agricultural practices—primarily the comprehensive use of nitrogen-based fertilizers to meet growing food demand—are directly related to the increase in N_2O emissions. The majority of anthropogenic N_2O emissions from agricultural soils generally result from biological processes such as microbial nitrification and denitrification. According to Braker and Conrad (2011), these changes are thought to be responsible for 56–70% of the world’s N_2O emissions and are driven by an overabundance of nitrogen in the soil, whether from manure or synthetic fertilizers (Syakila and Kroeze 2011). This trend is reflected in atmospheric data, which show a regular yearly rise of 0.77 ppb from 2000 to 2009 (World Meteorological Organization 2021).

Microbial nitrogen-cycling networks, including nitrification and denitrification pathways, regulate N_2O production in soils and respond strongly to soil conditions and nitrogen availability (Tian et al. 2014; Kuypers et al. 2018). Long-term and seasonal changes in gross nitrogen turnover can also influence N_2O emissions, especially in sensitive grassland and meadow systems (Hu et al. 2019).

Liao et al. (2024) claim that, through modifications in dissolved organic carbon and root exudates, nitrogen fertilization can alter the activity of genes related to nitrogen cycling, such as nxrA, narG, nirK/S, and nosZ (Li et al. 2024). However, under certain circumstances, nitrogen inputs may cause soil acidification, which decreases the number of important denitrification genes (Ning et al. 2015).

With approximately 10% of global anthropogenic GHG emissions coming from the sector, mostly from methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), agriculture has an important effect on climate change (Chataut et al. 2023; IPCC 2023). X. D. Wang et al. (2021) claim that, more than 60% of these agricultural N_2O sources are caused by fertilizer (Lin et al. 2023). Management techniques such as fertilizer application and straw mulching, which modify microbial activity and impact nitrogen cycling, also affect emissions in dryland agricultural systems (Lin et al. 2023; Liao et al. 2024).

According to Zhou and Butterbach-Bahl (2014), nitrogen fertilizer increases agricultural production by a rated 30–50%; nevertheless, over-application beyond crop needs might have negative environmental results. Shcherbak et al. (2014) and Guo et al. (2022) claim that these include non-point origin pollution, increased N_2O emissions, and soil acidification (Meng et al. 2005). By increasing microbial activity, nitrogen productivity raises the rates of nitrification and denitrification (Liu and Greaver 2009; Shen and Zhu 2022). Through accelerated plant growth, it may also improve soil organic carbon inputs, encouraging heterotrophic denitrification and further N_2O release (Henry et al. 2008).

In order to preserve yields and minimize greenhouse gas emissions, it is necessary to improve nitrogen utilization in agricultural processes. The development of climate-smart, sustainable agriculture practices requires a thorough understanding of how nitrogen fertilization techniques and residue management impact microbial nitrogen transformations and N_2O emissions (Zhao et al. 2025).

Compared to nitrate leaching, gaseous nitrogen losses are sometimes discussed in fewer detail in reviews of cropping systems, but these are not insignificant effects. Ammonia volatilization and N_2O emissions arise from the same reservoir of excess nitrogen that causes nitrate losses, and mitigation approaches may require trade-offs. For example, practices that maintain nitrogen in the soil may reduce nitrate transport but can increase gaseous losses if wet, carbon-rich or poorly drained micro-sites are generated. Therefore, nitrate leaching, ammonia volatilization, and N_2O emissions must be evaluated together.

Discussion

Nitrogen's role in agriculture is situated at the intersection of productivity and environmental responsibility. Although its use has led to higher crop yields globally, especially in intensive systems such as winter wheat agriculture, ineffective application causes dangerous problems. Important information about how nitrogen and nitrates are managed in agricultural systems has been summarized in this review, emphasizing both the physiological importance of nitrogen and the negative effects of incorrect management on the environment.

Also, large amounts of reactive nitrogen are lost to the environment through runoff, leaching, and emissions when main crops have low nitrogen use efficiency (NUE), which typically ranges between 30% and 50%. The accumulation of remaining nitrogen in soils, which may be useful for succeeding crops but is generally ignored in fertilization planning, exacerbates these losses. Inadequate management of this residual nitrogen's interaction with irrigation and rainfall can lead to nitrate leaching and greenhouse gas emissions.

Winter wheat serves as an example of how specific crop management techniques, including the timing of fertilizer application, the tillage process, and water regimes, have a direct impact on nitrogen dynamics. For example, split and deep placement of nitrogen fertilizer have demonstrated potential in increasing NUE and reducing nitrate losses. Meanwhile, nitrogen transformations and N_2O emissions are controlled by microbial processes, including nitrification and denitrification, which are greatly affected by soil conditions and the availability of organic matter.

New research access has been substantial in expanding our knowledge of nitrogen fluxes. Remote sensing, lysimetry, isotopic tagging, and process-based models have all helped to improve nitrogen tracking at the system and field levels. Uncertainties still exist, though, especially with regard to long-term nitrogen cycling, what happens to residual nitrogen, and how emissions vary based on soil type and climate zone.

Table 2. Priority options and trade-offs for nitrogen management.

Management option	Primary target	Potential co-benefits	Main trade-off or research need
Split or demand-based nitrogen application	Synchronize nitrogen supply with crop uptake.	Improves NUE and can reduce surplus nitrate.	Requires reliable weather, crop-growth and soil-nitrogen information.
Deep or banded placement	Place nitrogen closer to active root zones.	Can improve uptake and reduce surface losses.	Optimal depth varies with soil moisture, rooting depth, rainfall and genotype.
Cover crops and diversified rotations	Capture residual nitrogen and improve soil cover.	Reduces off-season nitrate leaching and improves soil structure.	Benefits depend on establishment success, termination timing and water availability.
Nitrification or urease inhibitors and controlled-release products	Slow nitrogen transformation or surface volatilization.	Can reduce selected loss pathways under favorable conditions.	Effectiveness is variable; cost, temperature, moisture and soil properties should be reported.
Precision monitoring and residual nitrogen accounting	Adjust rate and timing to field-specific nitrogen supply.	Supports integrated decisions across yield, water quality and greenhouse-gas mitigation.	Needs comparable indicators, calibration and long-term validation.

A change to site-specific, integrated nitrogen management is necessary to proceed. Understanding the importance of lagging nitrogen, improving monitoring strategies, and modifying NUE indicators to account for long-term nitrogen usage and retention will be essential to minimizing environmental effects without sacrificing productivity.

From a critical point of view, the strength of the reviewed literature lies in its description of the various nitrogen loss pathways, while its limitation is the integration of these pathways into farm-level decision-making practices. The primary objective, therefore, is not to reduce nitrogen input alone, but to combine nitrogen rate, source, application timing, and method with crop requirements, the amount of nitrogen remaining in the soil, the probability of gaseous losses, and rainfall. To support the comparative analysis, Table 2 summarizes the most significant nitrogen management practices with their expected agronomic and environmental benefits, as well as the remaining challenges that prevent their further implementation.

Conclusions

The complexity of nitrogen conduct in agricultural systems and the necessary need for sustainable management techniques are highlighted in this review. Although nitrogen is substantial for plant growth and productivity, its wasteful usage has dangerous negative effects on the environment, the economy, and agronomy. Nitrogen losses through leaching, volatilization, and emissions of strong greenhouse gases like N_2O have risen due to an over-reliance on chemical fertilizers, especially in cereal-based systems such as winter wheat. The growing of nitrogen use efficiency is complex, requiring an exact balance between crop demand, input satisfaction, and environmental preservation. Practices such as accurate nutrient placement, soil-specific management techniques, and tuning timing in fertilizing offer some practical means toward such a balance. The recognition and accumulation of residual N, and its integration into fertilizer recommendation schedules is no less important, as it could decrease inefficient input use and environmental losses.

Additionally, reliable analytical materials and broad field studies are necessary to understand nitrogen cycling fully and the effects of traditional fertilization practices. In the above context, it will be necessary to give these multi-disciplinary approaches that combine environmental modeling, soil science, agronomy, and policies related to sustainable nitrogen management. In summary, the environmental impact of agricultural practices must be considered when dealing with nitrogen management in a sustainable way, beyond the direct needs of crops. To be present at both high production and environmental management at the same time, global science-informed protocols are needed.

In summary, sustainable nitrogen management requires the combined consideration of productivity, nitrogen retention in the soil, nitrate leaching, ammonia volatilization, and N_2O emissions. In the future, the most beneficial research will focus on long-term field experiments that provide comparable nitrogen use efficiency indicators, quantify the various loss pathways in parallel, and define the management thresholds that can be applied to local soil, climatic, and crop production conditions.

Author contributions

CRediT: **Heba Albarnoti:** Data curation, Formal analysis, Writing – original draft; **Anikó Nyéki:** Conceptualization, Methodology, Supervision, Writing – original draft.

Abbreviation

N	Nitrogen
NO_3^-	Nitrate
NH_4^+	Ammonium
NO_2^-	Nitrite
N_2O	Nitrous Oxide
GHGs	Greenhouse Gases
NUE	Nitrogen Use Efficiency
NPK	Nitrogen, Phosphorus, and Potassium Fertilizers
SOM	Soil Organic Matter
IPCC	Intergovernmental Panel on Climate Change
ppm	Parts Per Million
kg N ha^{-1}	Kilograms of Nitrogen per Hectare
GIS	Geographic Information System
LCA	Life Cycle Assessment

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Data availability statement

The datasets obtained during this study are available from the corresponding author on reasonable request.

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