Pollution From Nitrogenous Fertilizers - Causes, Implications and Remedial Measures

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ABSTRACT

Nitrogenous fertilizers have played a major role in increasing agricultural productivity and supporting global food security. However, their excessive and inefficient use can result in considerable nitrogen losses to soil, water and the atmosphere, leading to groundwater contamination, eutrophication, ammonia volatilization and greenhouse gas emissions. The extent of nitrogen pollution is influenced by fertilizer type, application rate, soil characteristics, climate and crop-management practices. Improving nitrogen-use efficiency through precision fertilization, enhanced-efficiency fertilizers and integrated nutrient management can help minimize these losses. Biological approaches, appropriate fertilizer management, farmer awareness and supportive policies can further promote sustainable nitrogen use. Therefore, future nitrogen management should focus on achieving higher crop productivity while minimizing environmental and health impacts. A balanced approach to nitrogen use is essential for ensuring food security, environmental sustainability and long-term agricultural resilience.

INTRODUCTION:

Nitrogenous fertilizers have become an essential component of modern agriculture, providing crops with the nitrogen required for growth, chlorophyll formation, protein synthesis and ultimately higher yields. However, the benefits of

nitrogen fertilization can be accompanied by environmental pollution when fertilizers are applied in excess of crop requirements, at inappropriate times or using inefficient application methods. Nitrogen that is not taken up by crops can undergo various transformations and move through soil, water and the atmosphere as nitrate (NO_3^-), ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x) and other reactive nitrogen compounds. These losses can cause nitrate contamination of groundwater, eutrophication of rivers and lakes, ammonia and NO_x-related air pollution, greenhouse-gas emissions and changes in soil and ecosystem functioning. Excessive nitrogen inputs may also disturb soil microbial communities, contribute to biodiversity loss and create risks to human and animal health (Anas *et al*., 2020). Thus, nitrogen fertilizer pollution is not merely a problem of nutrient loss from agricultural fields but a wider environmental issue connecting agricultural productivity with the quality of air, water and soil. Addressing this challenge does not require abandoning nitrogen fertilizers; instead, it calls for improving nitrogen-use efficiency through balanced and site-specific fertilization, appropriate timing and placement, split application, precision nutrient management, enhanced-efficiency fertilizers, biological nitrogen fixation and improved crop and soil management. A better understanding of the causes, implications and remedial measures of nitrogen fertilizer pollution is therefore essential for achieving productive agriculture while protecting environmental quality and supporting long-term food security.

Major causes of pollution from nitrogenous fertilizers:

- Excessive fertilizer application: Applying more nitrogen than the crop can absorb leaves surplus nitrogen in the soil, increasing the possibility of nitrate leaching, runoff and gaseous losses.
- Imbalanced fertilizer use: Nitrogen is sometimes applied without adequately considering the crop's actual nutrient requirement, resulting in a mismatch between nitrogen supply and plant demand.
- Improper timing of application: Applying nitrogen before periods of heavy rainfall, irrigation or when crops have low nutrient demand increases the chance that nitrogen will move away from the root zone rather than being taken up by plants.
- Poor method of fertilizer placement: Broadcasting urea or other nitrogen fertilizers on the soil surface can increase ammonia volatilization, particularly under warm or alkaline conditions. Incorporation or appropriate placement can reduce such losses.
- Excessive irrigation and rainfall: Large amounts of water can transport soluble nitrate downward through the soil profile or across the soil surface, carrying nitrogen into groundwater, streams and other water bodies.
- Low nitrogen-use efficiency: A considerable fraction of applied nitrogen may fail to reach the harvested crop because nitrogen is transformed or lost through leaching, runoff, volatilization and denitrification. This makes inefficient fertilizer use an important driver of nitrogen pollution.
- Soil characteristics: Soil texture, pH, organic matter, drainage and water-holding capacity influence how nitrogen behaves after application. For example, nitrate is particularly vulnerable to leaching in permeable, light-textured soils.
- Unsuitable fertilizer selection: Different nitrogen fertilizers behave differently in soil. Surface-applied urea, for example, can produce substantial ammonia losses when

environmental and soil conditions favour volatilization.

- Inadequate crop cover and nutrient uptake: When crops are absent, poorly established or unable to absorb available nitrogen, more nitrogen remains vulnerable to movement with water or loss to the atmosphere.
- Poor irrigation and drainage management: Excessive or poorly scheduled irrigation can increase water movement below the root zone and thereby promote nitrate transport.
- Repetitive nitrogen application: Repeated applications that consistently exceed crop demand can gradually build up reactive nitrogen in agricultural soils, increasing the likelihood of subsequent environmental losses.
- Environmental conditions: Temperature, rainfall, soil moisture, pH and microbial activity regulate nitrogen transformations. Consequently, the same fertilizer application can produce very different losses under different field conditions.

Implications of nitrogenous fertilizer pollution:

The effects of nitrogenous fertilizer pollution become apparent when nitrogen escapes from agricultural fields and enters water, air and surrounding ecosystems. Nitrate (NO_3^-) is particularly important because it dissolves readily in water and can move downward through the soil with rainfall or irrigation, eventually contaminating groundwater. The maximum contaminant level for nitrate in drinking water is 10 mg/L when expressed as nitrate-nitrogen (NO_3^-–N) according to the US Environmental Protection Agency (EPA). When nitrate-contaminated water is consumed, nitrate can be converted into nitrite in the body. Nitrite interferes with the oxygen-carrying capacity of haemoglobin and may cause methaemoglobinaemia, commonly called *blue-baby syndrome*, particularly in infants. The WHO guideline value is 50 mg/L nitrate as NO_3^-, which is equivalent to approximately 11 mg/L as nitrate-nitrogen.

Nitrogen lost through surface runoff can enter rivers, lakes and reservoirs, where it stimulates excessive growth of algae and aquatic plants. This process, known as eutrophication, can reduce dissolved oxygen as the excess organic matter decomposes, creating stressful or even lethal conditions for fish and other aquatic organisms. At the same time, nitrogen fertilizers can contribute to air pollution. Surface-applied fertilizers, particularly urea, may release ammonia (NH_3), which can participate in the formation of fine particulate matter in the atmosphere. Another important consequence is the emission of nitrous oxide (N_2O) from nitrogen-rich soils. N_2O is a potent greenhouse gas and therefore links inefficient fertilizer management with climate change. Nitrogen losses can also contribute to nitrogen oxide (NO_x) pollution and atmospheric nitrogen deposition, which may alter natural ecosystems and reduce biodiversity.

Long-term and excessive nitrogen application can further contribute to soil acidification and changes in soil microbial communities, affecting nutrient availability and normal soil functioning. Thus, nitrogen fertilizer pollution is not simply a matter of losing fertilizer from the field; it represents a chain of connected impacts—from nitrate leaching and groundwater contamination to human health risks, eutrophication, air pollution, greenhouse-gas emissions, soil degradation and biodiversity loss. As emphasized by the WHO, controlling nitrate exposure in drinking water is particularly important for protecting infants from methaemoglobinaemia (Pan *et al.,* 2022).

Remedial measures for pollution from nitrogenous fertilizers:

Reducing nitrogen fertilizer pollution does not mean stopping fertilizer use; rather, the aim is to ensure that more of the applied nitrogen is taken up by crops and less is lost to the environment. The following measures can help achieve this:

- Follow the 4R principle: Apply the right source, right rate, right time and right place so that nitrogen supply matches crop demand as closely as possible.
- Apply nitrogen according to crop requirement: Soil testing, crop nutrient requirements and expected yield should be considered before deciding the fertilizer dose. Avoiding unnecessary nitrogen application is one of the simplest ways to reduce losses.
- Use split application: Instead of applying the entire nitrogen dose at once, divide it into several applications according to crop growth stages. This keeps nitrogen available when plants need it and reduces the amount left vulnerable to leaching and gaseous losses.
- Improve fertilizer placement: Placing fertilizer close to the crop root zone rather than spreading it uniformly over the soil surface can improve nitrogen uptake and reduce losses, particularly ammonia volatilization.
- Adopt enhanced-efficiency fertilizers: Slow-release and controlled-release fertilizers, polymer-coated fertilizers, sulphur-coated fertilizers and nitrification or urease inhibitors can regulate nitrogen release or slow particular transformation pathways, helping synchronize nitrogen availability with crop demand (Rajonee *et al*., 2026).
- Use precision nitrogen management: GPS-based application, crop sensors, remote sensing, variable-rate technology and digital soil information can help identify differences in crop and soil nitrogen requirements within a field, allowing fertilizer to be applied more precisely.
- Manage irrigation carefully: Irrigation should be scheduled according to crop water requirements. Avoiding excessive irrigation reduces the downward movement of nitrate beyond the root zone and limits nitrogen losses through drainage.
- Maintain adequate crop and plant cover: Cover crops can capture residual nitrogen remaining in the soil after the main crop is harvested. This reduces the amount of nitrate available for leaching during periods when the field would otherwise remain bare.
- Promote biological nitrogen fixation: Legume crops and beneficial nitrogen-fixing microorganisms can supply part of the nitrogen requirement naturally, reducing dependence on synthetic nitrogen fertilizers.
- Recycle organic nutrient sources: Properly managed farmyard manure, compost, crop residues and other organic resources can return nutrients to the soil. Their nutrient content should, however, be considered when calculating fertilizer requirements to avoid excessive nitrogen inputs.
- Improve crop residue management: Returning suitable crop residues to the soil can support nutrient cycling and improve soil organic matter. Residue management should be coordinated with fertilizer application so that nitrogen is neither unnecessarily accumulated nor immobilized.

- Use nitrification and urease inhibitors where appropriate: These products can slow the conversion of ammonium to nitrate or reduce the rapid breakdown of urea, thereby decreasing specific nitrogen-loss pathways.

- Protect water bodies with vegetative buffer zones: Grass strips, riparian vegetation and other buffer areas between agricultural fields and water bodies can intercept nutrient-rich runoff before it reaches streams, ponds and rivers.

- Integrate organic and inorganic nutrient sources: Combining fertilizers with well-managed organic nutrient sources can improve nutrient availability and soil health while reducing excessive dependence on synthetic nitrogen.

- Monitor soil and water regularly: Periodic testing of soil nitrate, groundwater and surface water can identify emerging nitrogen losses and help farmers adjust fertilizer and irrigation practices before pollution becomes severe.

Future Perspectives:

- Precision nitrogen management: Integration of remote sensing, GIS, sensors and artificial intelligence can enable site-specific fertilizer application based on actual crop and soil requirements.

- Development of efficient fertilizers: Greater use of slow-release, controlled-release, coated and other enhanced-efficiency fertilizers can reduce nitrogen losses while maintaining crop productivity.

- Biological and integrated approaches: Combining biofertilizers, biological nitrogen fixation, organic inputs and mineral fertilizers can improve nitrogen-use efficiency and reduce dependence on excessive synthetic fertilizers.

- Climate-smart nitrogen management: Future practices should focus on reducing NO_3^- leaching, NH_3 volatilization, N_2O and NO_x emissions, while adapting fertilizer management to changing climate and rainfall patterns.

- Sustainable policies and monitoring: Stronger nutrient-management policies, regular soil and water monitoring, farmer awareness and region-specific fertilizer recommendations will be essential for balancing food production with environmental protection.

CONCLUSION:

Nitrogenous fertilizers have played a vital role in increasing agricultural productivity, but their excessive and inefficient use has become an important source of environmental pollution. Nitrogen losses through leaching, runoff, volatilization and gaseous emissions can contaminate water, degrade soil quality and contribute to air pollution, eutrophication and greenhouse gas emissions, with potential risks to human and ecosystem health. Therefore, the focus should shift from simply increasing nitrogen application to improving nitrogen-use efficiency (Tufaila *et al*., 2024). Adoption of precision nutrient management, enhanced-efficiency fertilizers, integrated nutrient management and biological approaches, supported by farmer awareness and effective policies, can substantially reduce nitrogen losses. Sustainable nitrogen management is ultimately essential for achieving a balance between food security, agricultural productivity and environmental protection.

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