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LONG-TERM FATE OF NITROGEN FERTILIZERS IN AGRICULTURAL SOILS: IMPLICATIONS FOR SOIL HEALTH AND ENVIRONMENTAL SUSTAINABILITY

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Nitrogen fertilizers play a crucial role in enhancing agricultural productivity and supporting global food security. However, long-term and excessive application of nitrogen fertilizers can negatively affect soil health, water quality, and environmental sustainability. In agricultural soils, nitrogen undergoes several transformation processes including mineralization, ammonification, nitrification, immobilization, denitrification, and volatilization, which influence its availability to plant and its potential losses from the soil system. A major portion of applied nitrogen is utilized by crops, while the remaining fraction may accumulate in soil organic matter or lost through nitrate leaching, surface runoff, and gaseous emissions. These losses contribute to groundwater contamination, eutrophication of aquatic ecosystems, soil acidification, nutrient imbalance, and greenhouse gas emissions. Sustainable nitrogen management practices such as balanced fertilization, precision agriculture, conservation tillage, cover cropping and controlled-release fertilizers can improve nitrogen use efficiency and reduce environmental impacts. Understanding the long-term fate of nitrogen fertilizers is therefore essential for sustainable agricultural production and environmental protection.

Nitrogen fertilizers are indispensable for modern agriculture because they significantly increase crop productivity and support global food security. Rapid population growth and increasing food demand have intensified the use of synthetic nitrogen fertilizers across agricultural systems worldwide. However, continuous and excessive application of nitrogen fertilizers has created serious concerns regarding soil health, environmental sustainability, and water quality (Vitousek *et al*., 1997). Nitrogen added to agricultural soils undergoes several biological and chemical transformations that determine its availability to plants and its eventual fate in the environment.

In agricultural soils, nitrogen exists in multiple forms and continuously cycles through the atmosphere, plants, microorganisms, and soil organic matter. While a major proportion of applied nitrogen is absorbed by crops, a considerable fraction remains in the soil or is lost through volatilization, denitrification, runoff, and leaching. These losses reduce nitrogen use efficiency and contribute to environmental pollution (Giordano *et al*., 2021). Long-term fertilizer use also influences soil pH, nutrient balance, microbial activity, and soil organic carbon dynamics.

Studies conducted at long-term experimental sites have shown that a significant portion of applied fertilizer nitrogen becomes incorporated into soil organic matter and may remain in the soil for several years. Over time, this residual nitrogen can be gradually released through mineralization and may contribute either to crop nutrition or environmental contamination (Sebilo *et al*., 2013). Therefore, understanding the fate of nitrogen fertilizers in agricultural soils is essential for developing sustainable nutrient management practices that optimize productivity while minimizing ecological risks.

Nitrogen Transformation Processes in Soil

Nitrogen in agricultural soils undergoes continuous transformation through microbial and biochemical processes. These transformations determine the availability of nitrogen to crops as well as the potential losses from soil systems.

Mineralization is the process through which organic nitrogen compounds are converted into inorganic forms. During this process, soil microorganisms decompose proteins, amino acids, nucleic acids, and other organic materials to release ammonium. This transformation is essential for maintaining soil fertility because it converts unavailable organic nitrogen into plant-available forms (Jenkinson and Parry, 1989).

Ammonification is a major component of mineralization in which organic nitrogen compounds are converted into ammonium ions. The released ammonium may either be absorbed by plants or undergo nitrification. Nitrification is a microbial process in which ammonium is oxidized first to nitrite and then to nitrate by nitrifying bacteria. Although nitrate is readily available for crop uptake, it is highly mobile and susceptible to leaching losses.

Immobilization is the reverse process of mineralization. During immobilization, soil microorganisms absorb inorganic nitrogen from the soil solution and convert it into microbial biomass. This temporarily reduces nitrogen availability to crops. Balance between mineralization and immobilization depends largely on the carbon-to-nitrogen ratio of soil organic matter.

Denitrification is another important nitrogen transformation process that occurs under anaerobic or waterlogged soil conditions. In this process, nitrate is reduced to gaseous forms such as nitric oxide, nitrous oxide, and nitrogen gas. Denitrification contributes significantly to nitrogen loss from agricultural systems and is also a major source of nitrous oxide emissions.

Volatilization refers to the loss of ammonia gas from surface-applied nitrogen fertilizers, especially urea and ammonium-based fertilizers. This process is influenced by soil pH, temperature, moisture, and wind conditions. Ammonia volatilization reduces fertilizer efficiency and contributes to atmospheric pollution.

Fate of Nitrogen Fertilizers in Agricultural Soil

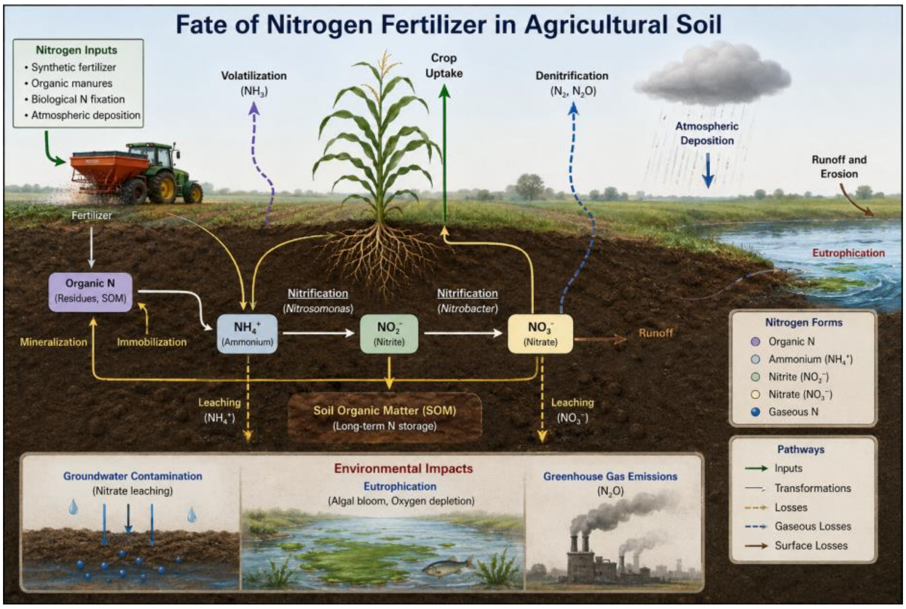
The fate of nitrogen fertilizer in agricultural soil depends on soil properties, climate, crop demand, and management practices. Once applied, nitrogen fertilizers may be absorbed by plants, retained in soil organic matter, transformed into gaseous forms or lost through leaching and runoff.

Research using isotopically labelled nitrogen fertilizers has demonstrated that approximately 40–60 percent of applied nitrogen is taken up by crops during the growing season. A substantial proportion of the remaining fertilizer nitrogen becomes incorporated into soil organic matter and microbial biomass (Sebilo *et al*., 2013). This residual nitrogen can persist in soil for many years and may gradually become available through mineralization.

Nitrate is highly soluble and easily transported through the soil profile with percolating water. Under conditions of heavy rainfall or excessive irrigation, nitrate leaching can contaminate groundwater resources. Elevated nitrate concentrations in drinking water are associated with human health problems and ecological degradation (Ju *et al*., 2006).

Nitrogen may also be lost through surface runoff, particularly in poorly managed agricultural fields. Runoff carrying nitrate and ammonium contributes to eutrophication of rivers, lakes, and coastal ecosystems. Excessive nutrient loading stimulates algal blooms and reduces dissolved oxygen levels, creating aquatic dead zones (Zhao *et al*., 2012).

Long-term fertilizer application can also lead to the accumulation of residual nitrogen in soil. While this residual nitrogen may support crop growth in subsequent seasons, it also increases the risk of environmental losses. The long-term legacy of fertilizer nitrogen therefore remains an important concern in intensive agricultural systems.



Long-Term Effects of Nitrogen Fertilizer Application

Continuous nitrogen fertilizer application has profound effects on soil health, soil fertility, and environmental quality. One of the most important consequences is soil acidification. Ammonium-based fertilizers release hydrogen ions during nitrification, gradually lowering soil pH. Acidification reduces the availability of essential nutrients such as calcium, magnesium, and phosphorus while increasing the solubility of toxic elements like aluminum and manganese.

Long-term nitrogen application can also create nutrient imbalances within the soil. Excessive nitrogen availability may suppress the uptake of potassium, phosphorus, and micronutrients, resulting in nutrient deficiencies and reduced crop quality. Such imbalances often affect plant growth, root development, and resistance to pests and diseases.

Another important consequence is the decline in soil organic matter. High nitrogen inputs stimulate microbial activity and accelerate decomposition of organic materials. Although this may temporarily increase nutrient release, continuous decomposition eventually reduces soil organic carbon content. Declining organic matter negatively affects soil aggregation, water retention, aeration, and overall soil structure (Giordano *et al*., 2021).

Nitrogen fertilizers also influence soil microbial communities. Long-term application may alter the diversity and activity of beneficial microorganisms involved in nutrient cycling and soil health maintenance. Reduced microbial diversity can weaken soil resilience and ecological stability (Dietz *et al*., 2013).

In addition, excessive nitrogen application increases the risk of greenhouse gas emissions. Nitrous oxide produced during nitrification and denitrification is a potent greenhouse gas with a global warming potential much higher than carbon dioxide. Agriculture is therefore considered a major contributor to atmospheric nitrous oxide emissions.

Environmental Implications

The environmental consequences of long-term nitrogen fertilizer use have become a major global concern. Nitrate contamination of groundwater and surface water is one of the most serious issues associated with intensive agriculture. Increased nitrate concentrations in water bodies have been linked to eutrophication, harmful algal blooms, and deterioration of aquatic ecosystems (Ju *et al*., 2006).

Nitrogen losses also contribute to atmospheric pollution. Ammonia volatilization affects air quality and may contribute to acid rain formation. Similarly, nitrous oxide emissions from agricultural soils contribute significantly to global climate change and ozone layer depletion.

Excessive nitrogen use further increases the risk of soil degradation and erosion. Continuous fertilizer application without balanced nutrient management may weaken soil structure and reduce the capacity of soils to retain water and nutrients. These changes ultimately reduce long-term agricultural productivity.

Several studies have emphasized that increasing anthropogenic nitrogen inputs have significantly altered the natural nitrogen cycle in terrestrial and aquatic ecosystems (Vitousek *et al*., 1997). The widespread use of synthetic fertilizers, combined with land-use changes and intensive cropping systems, has accelerated nitrogen losses to the environment.

Mitigation Strategies and Sustainable Nitrogen Management

Improving nitrogen use efficiency is essential for achieving sustainable agricultural production. Several management strategies can help reduce nitrogen losses and enhance fertilizer efficiency. Balanced fertilization based on soil testing is one of the most effective approaches. Applying fertilizers according to crop demand prevents excessive nitrogen accumulation in soil. The adoption of the 4R nutrient stewardship principles—right source, right rate, right time, and right placement—can significantly improve nitrogen management (Ladha *et al*., 2005).

Precision agriculture technologies also offer new opportunities for efficient fertilizer application. Variable-rate application systems, chlorophyll meters, and sensor-based nutrient management tools help farmers apply fertilizers more accurately according to field variability and crop requirements.The use of slow-release fertilizers, controlled-release fertilizers, and nitrification inhibitors can reduce nitrogen losses through volatilization and leaching. Biological nitrification inhibition has also gained importance for improving nitrogen retention and minimizing environmental contamination (Dietz *et al*., 2013).

Conservation tillage, crop rotation, and cover cropping are important sustainable practices that improve soil organic matter and nitrogen retention. Cover crops absorb residual soil nitrogen during fallow periods and release it gradually after decomposition. Reduced tillage also helps maintain soil structure and minimize erosion.

Proper irrigation management is another key factor in reducing nitrate leaching and denitrification losses. Excessive irrigation creates anaerobic conditions that promote denitrification and increase nitrogen movement below the root zone. Efficient irrigation scheduling can therefore improve both water and nitrogen use efficiency.

Conclusion

The fate of long-term nitrogen fertilizer in agricultural soils is controlled by a complex interaction of biological, chemical, and environmental processes. Nitrogen fertilizers are essential for sustaining crop productivity and ensuring food security, yet their excessive and unbalanced use can negatively affect soil health, water quality, and the atmosphere.

A substantial proportion of fertilizer nitrogen is lost through leaching, volatilization, denitrification, and runoff, reducing fertilizer efficiency and increasing environmental pollution. Long-term nitrogen application can lead to soil acidification, nutrient imbalance, decline in soil organic matter, and greenhouse gas emissions.

Adopting sustainable nitrogen management practices is essential for maintaining soil fertility and minimizing environmental risks. Precision agriculture, balanced fertilization, cover cropping, conservation tillage, and improved irrigation management can significantly enhance nitrogen use efficiency. Continued research and monitoring are necessary to better understand the long-term behavior of fertilizer nitrogen and to develop environmentally responsible nutrient management strategies for future agricultural systems.

References

Dietz, M., Machill, S., Hoffmann, H.C. & Schmidtke, K. (2013). Inhibitory effects of Plantago lanceolata L. on soil N mineralization. *Plant and Soil*, 368, 445–458.

Giordano, M., Petropoulos, S.A., & Rouphael, Y. (2021). The fate of nitrogen from soil to plants: Influence of agricultural practices in modern agriculture. *Agriculture*, 11(10), 944.

Jenkinson, D.S., & Parry, L.C. (1989). The nitrogen cycle in the Broadbalk wheat experiment: A model for the turnover of nitrogen through the soil microbial biomass. *Soil Biology and Biochemistry*, 21(4), 535–541.

Ju, X.T., Kou, C.L., Zhang, F.S., & Christie, P. (2006). Nitrogen balance and groundwater nitrate contamination among intensive cropping systems on the North China Plain. *Environmental Pollution*, 143(1), 117–125.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85–156.

Sebilo, M., Mayer, B., Nicolardot, B., Pinay, G., & Mariotti, A. (2013). Long-term fate of nitrate fertilizer in agricultural soils. *Proceedings of the National Academy of Sciences*, 110(45), 18185–18189.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., & Melillo, J.M. (1997). Human domination of Earth's ecosystems. *Science*, 277(5325), 494–499.

Zhao, X., Zhou, Y., Min, J., Wang, S., Shi, W., & Xing, G. (2012). Nitrogen runoff dominates water nitrogen pollution from rice–wheat rotation in the Taihu Lake region of China. *Agriculture, Ecosystems & Environment*, 156, 1–11.