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Soil Nitrogen Paradox in Punjab, Pakistan: High Urea Inputs, Low Nitrogen Recovery, and Pathways to Sustainable Intensification

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ABSTRACT

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Punjab, Pakistan, is characterized by intensive nitrogen (N) fertilizer use, particularly urea, yet the substantial gaps remain between N inputs and crop N recovery. This review examines the paradox of high N fertilizer consumption, low nitrogen use efficiency (NUE), and persistent crop productivity constraints across the major irrigated and rainfed agroecosystems of Punjab. Evidence from published studies indicates that N recovery in major cropping systems commonly remains around 30–35%, while substantial N losses occur through ammonia (NH₃) volatilization, nitrate (NO₃[−]) leaching, denitrification, and other transformation pathways. The problem is intensified by widespread calcareous and alkaline soils, low soil organic matter, imbalanced fertilization, excessive or poorly timed N application, limited soil testing, and inadequate synchronization between N supply and crop demand. Literature also indicates that a large proportion of N is frequently applied as basal fertilizer, increasing the risk of losses before periods of maximum crop uptake. Reported agronomic N-use efficiencies vary considerably among crops and production systems, reflecting differences in soil properties, climate, irrigation, fertilizer practices, and crop management. The review further evaluates evidence for improved N management approaches, including the 4R Nutrient Stewardship framework, soil-test-based fertilization, split and demand-driven N application, urease and nitrification inhibitors, polymer-coated and other controlled-release fertilizers, precision nutrient management, and crop-based diagnostic tools such as SPAD and leaf colour charts. Collectively, published evidence suggests that integrating these approaches can improve N recovery and agronomic efficiency while reducing reactive N losses without necessarily increasing total N inputs. Particular attention is given to the contrasting challenges of irrigated and rainfed systems, where rainfall variability and limited moisture availability complicate N synchronization. The review identifies policy, economic, extension, and adoption barriers that constrain the transition from high-input fertilizer management toward efficient N stewardship. Sustainable intensification of Punjab agriculture therefore requires an integrated strategy combining improved fertilizer technologies, site-specific N recommendations, farmer capacity building, soil testing, and supportive policy measures to enhance NUE, maintain crop productivity, and reduce environmental N losses.

Introduction

Nitrogen is the most yield-limiting nutrient in cereal-based production systems worldwide and contributes significantly to global food security (Erisman et al., 2008). In Pakistan, agriculture accounts for approximately 21% of gross domestic product and supports the livelihoods of nearly two-thirds of the rural population. Punjab province contributes more than 75% of national wheat production and nearly 70% of total fertilizer consumption, making it the agricultural backbone of the country (Government of Pakistan, 2024).

Nitrogen fertilizer consumption in Pakistan has increased dramatically since the Green Revolution. Urea constitutes more than 85% of total N fertilizer use, with average application rates exceeding 140 kg N ha⁻¹ in intensive wheat-rice cropping systems. Despite these inputs, crop recovery of applied N remains remarkably low, averaging only 30–35%, considerably below the global average of 50% (Raun and Johnson, 1999; Ladha et al., 2005).

This discrepancy between increasing fertilizer inputs and stagnant N recovery creates a paradoxical situation where farmers continue applying more N while obtaining diminishing agronomic returns. Simultaneously, environmental losses through volatilization, leaching, and greenhouse gas emissions are increasing. Understanding the causes and solutions to this N paradox is critical for achieving sustainable agricultural intensification in Punjab.

Table 1. Literature evidence supporting the soil nitrogen paradox in Punjab, Pakistan

Study/Source	Location	Key Findings	Relevance to Soil N Paradox
Malik et al. (1975) as cited by Qureshi et al. (2000)	Punjab, Pakistan	Analysis of 6,000 soil samples showed 61.8% of soils were deficient in organic matter.	Low SOM limits N mineralization and native N supply despite fertilizer use.
Rashid (1994) as cited by Ahmad et al.	Chakwal, Punjab	Organic matter ranged from 0.2–1.3% in surface soils; most soils were deficient.	Rainfed soils possess poor N-supplying capacity and weak nutrient cycling.
Soil fertility mapping of Pakistan	Punjab Province	Approximately 93% of agricultural soils contained <1% SOM; median SOM was 0.66%.	Extremely low SOM necessitates continuous N fertilizer application while reducing NUE.
World Bank (2000)	Punjab, Pakistan	Only about 4% of surveyed Punjab soils had moderate to adequate organic matter levels.	SOM depletion constrains N, C and S cycling and reduces fertilizer efficiency.
Punjab Soil Fertility Status Mapping	Punjab Province	Soil N status was generally classified as poor, while most soils contained <1% organic matter.	Demonstrates widespread N deficiency despite intensive cropping and fertilizer use.
Shahzad et al. (2025)	Punjab Cropping Systems	Soil organic matter ranged only from 0.45–0.57%, while total N ranged from 0.01–0.03%; deficiencies persisted across cropping systems.	Indicates chronic depletion of soil N reserves under conventional production systems.
Mapping of Cotton Soils in Southern Punjab	Rahim Yar Khan	Soils contained 6.1–12% CaCO ₃ , pH 8.15–8.80, and 57% samples had OM <0.86%.	Alkaline-calcareous conditions enhance NH ₃ volatilization losses from urea.
Punjab State of Environment Report (2022)	Punjab Province	Most soils contain only 0–1% organic matter because of intensive tillage, high temperature, and inadequate residue return.	Continuous SOM depletion undermines long-term N availability and NUE.
Khan et al. (2021)	Pakistan/Punjab	About 90% of agricultural soils were deficient in SOM (<1%), and N fertilization was required across most cropping areas.	High dependence on synthetic N fertilizer reflects insufficient native soil N supply.
Soil Survey of Punjab	Punjab Province	Most agricultural soils are alkaline-calcareous and routinely monitored for N deficiency.	Soil properties inherently favor N losses and low fertilizer recovery.

Nitrogen Status of Punjab Soils

Punjab soils are predominantly alkaline-calcareous, containing significant quantities of calcium carbonate and exhibiting pH values ranging from 7.8 to 8.6. Such conditions reduce nutrient availability and accelerate ammonia volatilization following urea application (Havlin et al., 2017). Long-term soil fertility surveys indicate widespread nitrogen deficiency throughout the province. More than 70% of agricultural soils contain available N concentrations below the critical threshold required for optimum crop growth. Nitrogen deficiency is particularly severe in the rainfed Pothohar region, where alkaline-calcareous soils,

low organic matter content, erratic rainfall, and erosion further constrain nutrient cycling and crop productivity (Ahmed and Rashid, 2003; Khan and Joergensen, 2006; SFRI, 2021).

Low soil organic matter (SOM) is considered one of the most critical factors responsible for N deficiency in the agricultural soils of Punjab. Most cultivated soils of the province contain less than 1% SOM, while values below 0.86% are classified as poor according to the Soil Fertility Research Institute (SFRI) fertility guidelines. Such levels are substantially lower than the 2–3% SOM generally considered desirable for maintaining sustainable soil productivity and nutrient cycling in arid and semi-arid agroecosystems.

The depletion of SOM is primarily attributed to intensive cultivation, limited incorporation of crop residues, low application of organic amendments, high summer temperatures, and rapid decomposition rates under alkaline-calcareous conditions. As soil organic matter constitutes the principal reservoir of organically bound nitrogen, its decline directly reduces the soil's capacity to mineralize and supply plant-available N throughout the growing season. Furthermore, low SOM adversely affects soil microbial biomass and enzymatic activity, resulting in slower nutrient turnover and reduced NUE of applied fertilizers (Brady and Weil, 2017; Havlin et al., 2017).

Beyond nutrient supply, soil organic matter plays a vital role in maintaining soil structure, aggregation, water-holding capacity, cation exchange capacity, and nutrient buffering. The widespread occurrence of SOM levels below 1% in Punjab soils has therefore contributed to diminished biological activity, poor moisture retention, increased susceptibility to erosion, and reduced resilience of cropping systems to climatic stresses. These constraints are particularly pronounced in the rainfed Pothohar region, where erratic rainfall and soil erosion further accelerate organic matter depletion and limit nitrogen cycling. Consequently, improving SOM through integrated nutrient management, residue recycling, compost application, green manuring, biochar incorporation, and enhanced-efficiency fertilizers is essential for restoring soil fertility and enhancing sustainable crop productivity in Punjab. (Khan et al., 2017; Lal, 2020).

Sources of the Nitrogen Paradox

Alkaline-Calcareous Soil Conditions

The calcareous nature of Punjab soils accelerates conversion of ammonium to ammonia gas following urea hydrolysis. High soil pH, elevated temperatures, and surface fertilizer placement create ideal conditions for volatilization losses. Studies conducted in South Asian calcareous soils have reported ammonia losses ranging from 20–40% of applied N (Zaman et al., 2013).

Low Soil Organic Matter

Organic matter serves as a major reservoir of soil nitrogen. Continuous cultivation, residue removal, and inadequate organic amendments have depleted soil carbon stocks across Punjab. Reduced microbial biomass and mineralization rates limit the supply of plant-available N and decrease overall NUE (Lal, 2004).

Inefficient Fertilizer Management

A large proportion of farmers apply N fertilizer in one or two large basal doses at planting. Such practices expose N to prolonged periods of loss before crop uptake reaches peak demand. Synchronization between crop N requirements and fertilizer application remains poor across most production systems.

Limited Soil Testing and Precision Agriculture

Despite increasing fertilizer costs, adoption of soil testing remains low. Farmers frequently rely on generalized fertilizer recommendations that fail to account for field-specific variability in nutrient status. Consequently, over-application and under-application often occur simultaneously within the same production regions.

Nitrogen Loss Pathways

Nitrogen losses from agricultural soils represent the principal cause of low NUE in Punjab's cereal-based production systems. The predominance of alkaline-calcareous soils, high temperatures during fertilizer application, intensive irrigation practices, and poor synchronization between N supply and crop demand collectively accelerate N losses through volatilization, leaching, denitrification, and immobilization. These loss pathways substantially reduce fertilizer recovery by crops while increasing environmental pollution and greenhouse gas emissions (Ladha et al., 2005; Zhang et al., 2015).

Ammonia Volatilization

Ammonia (NH_3) volatilization is considered the dominant pathway of N loss in the alkaline-calcareous soils of Punjab. Following urea application, soil urease rapidly hydrolyzes urea into ammonium carbonate, causing a temporary increase in soil pH around fertilizer granules. Under alkaline conditions ($\text{pH} > 7.5$), a significant proportion of ammonium (NH_4^+) is converted to gaseous ammonia (NH_3), which escapes into the atmosphere (Sommer et al., 2004).

The risk of volatilization is further enhanced by high temperatures, low soil organic matter, surface broadcasting of urea, and delayed irrigation. Studies conducted in South Asian wheat-rice systems have reported ammonia losses ranging from 20 to 40% of applied N, while losses exceeding 50% have been observed under unfavorable management conditions (Zaman et al., 2013; Cantarella et al., 2018). Besides reducing fertilizer efficiency, ammonia emissions contribute to atmospheric particulate matter formation, ecosystem eutrophication, and indirect nitrous oxide production.

Nitrate Leaching

Nitrate (NO_3^-) leaching constitutes another major pathway of N loss, particularly in irrigated production systems and coarse-textured soils. Following nitrification, ammonium-derived nitrogen is converted into nitrate, a highly mobile anion that is not strongly retained by negatively charged soil colloids. Excessive irrigation or intense rainfall can transport nitrate below the crop rooting zone, rendering it unavailable for plant uptake (Cameron et al., 2013).

Leaching losses are especially pronounced in rice-wheat systems where irrigation frequencies are high and nitrogen applications often exceed crop demand. Beyond agronomic losses, nitrate leaching poses significant environmental concerns through contamination of groundwater resources and deterioration of drinking water quality. Elevated nitrate concentrations in groundwater have been linked with ecological degradation and human health risks in many agricultural regions worldwide (Di and Cameron, 2002).

Denitrification

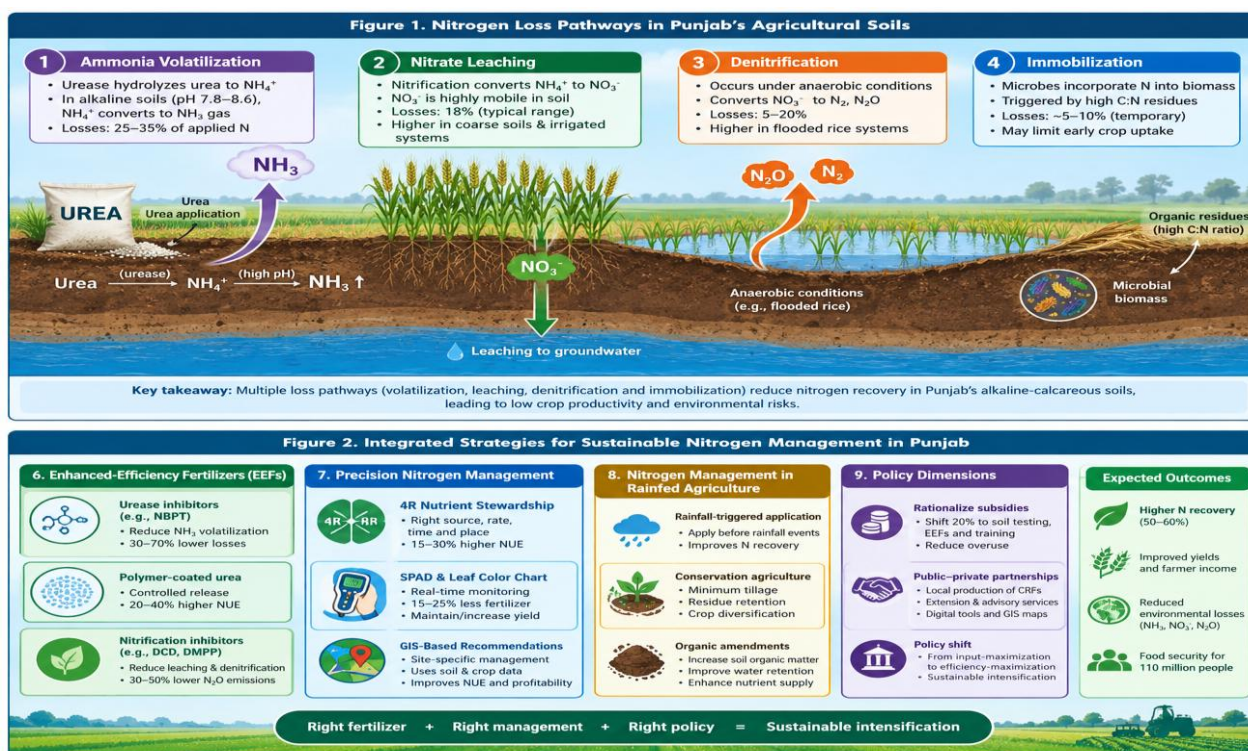
Denitrification is a biologically mediated process whereby nitrate is reduced to gaseous forms of N, including nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen (N_2), under oxygen-limited conditions. This process is particularly important in flooded rice fields, poorly drained soils, and compacted agricultural lands where temporary anaerobic conditions develop following irrigation or rainfall events (Firestone and Davidson, 1989).

Although denitrification contributes to the natural N cycle, excessive losses reduce fertilizer recovery and increase emissions of nitrous oxide, a greenhouse gas with a global warming potential approximately 273 times greater than carbon dioxide over a 100-year period (IPCC, 2021). Nitrogen losses through denitrification in cereal production systems generally range from 5 to 20% of applied fertilizer N depending on soil moisture status, carbon availability, and fertilizer management practices (Shcherbak et al., 2014).

Immobilization

Microbial immobilization occurs when soil microorganisms assimilate inorganic N into their biomass during decomposition of organic materials with high carbon-to-nitrogen ratios. Crop residues such as wheat straw and maize stover often stimulate temporary immobilization of fertilizer N, reducing its short-term availability to crops (Recous et al., 1995).

Although immobilization is generally viewed as a temporary loss pathway because N can later be mineralized and released back into the soil, excessive immobilization during critical crop growth stages may reduce N uptake and limit productivity. In low organic matter soils of Punjab, immobilization often interacts with other N transformation processes, influencing overall NUE and fertilizer recovery.



Nitrogen Use Efficiency across Cropping Systems

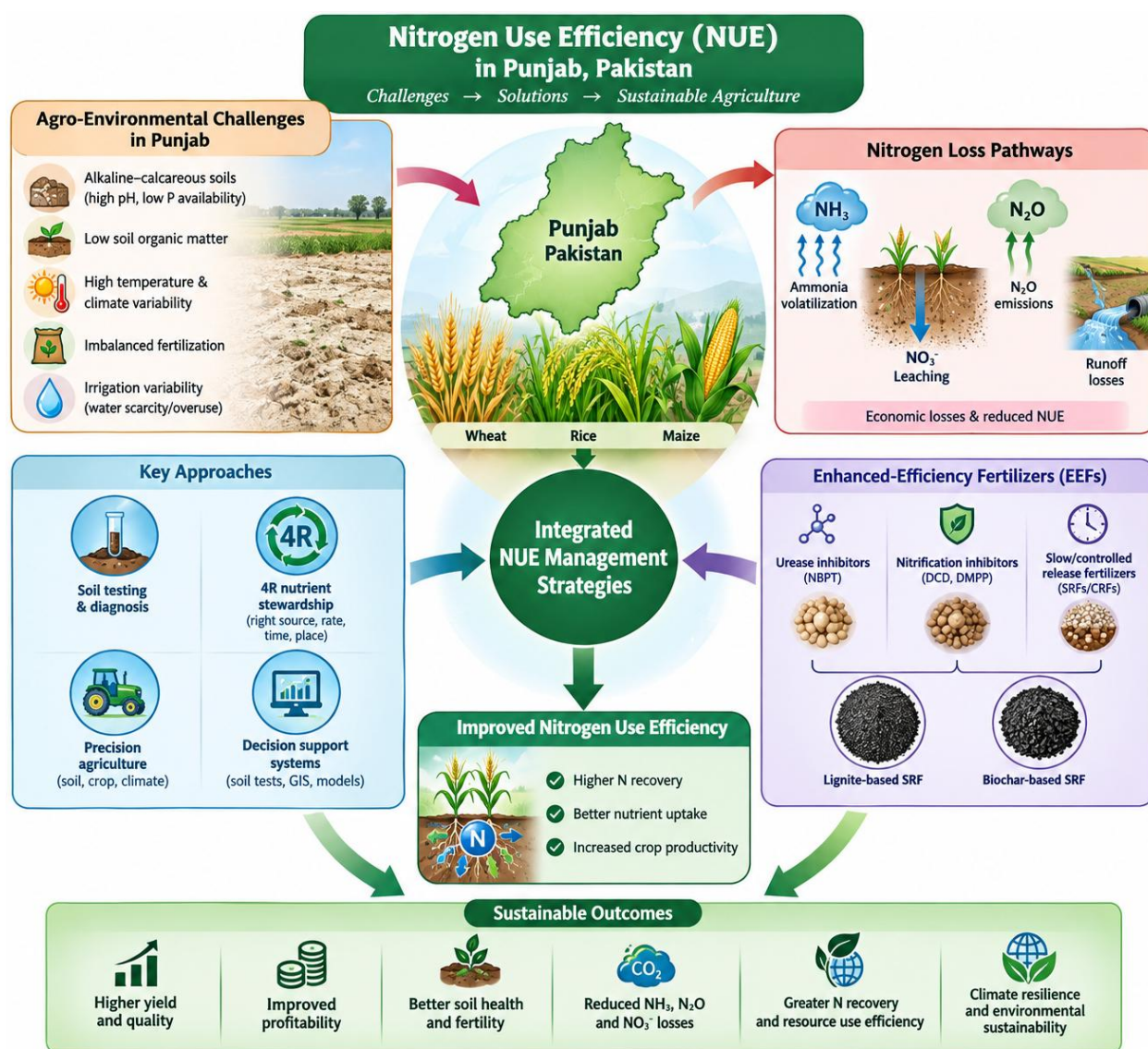
Nitrogen use efficiency varies considerably among crops, production systems, soil types, and management practices. Agronomic efficiency (AE), recovery efficiency (RE), physiological efficiency (PE), and partial factor productivity (PFP) are commonly used indicators for evaluating crop responses to applied nitrogen (Raun and Johnson, 1999).

Among major field crops cultivated in Punjab, maize generally exhibits the highest NUE due to its extensive root system, high photosynthetic capacity, and greater ability to synchronize nitrogen uptake with crop demand. Reported agronomic efficiencies frequently exceed $20 \text{ kg grain kg}^{-1} \text{ N}$ under well-managed conditions. In contrast, rice and cotton often display lower efficiencies because of substantial nitrogen losses through volatilization, denitrification, and leaching (Cassman et al., 2002).

Wheat, the principal staple crop of Pakistan, typically recovers only 30–40% of applied N despite receiving substantial fertilizer inputs. Consequently, wheat yields in many districts remain considerably below attainable yield levels. Similar trends have been reported for rice, sugarcane, and cotton, where increasing fertilizer use has not resulted in proportional yield gains due to declining NUE and inefficient nutrient management (Ladha et al., 2005).

The gap between actual and attainable NUE is particularly evident in rainfed regions of Pothohar, where erratic rainfall, low soil organic matter, and poor nutrient retention further constrain nitrogen recovery. Studies suggest that NUE in rainfed systems may be 30–40% lower than in irrigated environments because fertilizer application is often poorly synchronized with rainfall events and crop nitrogen demand (Fageria and Baligar, 2005).

Improving NUE across Punjab's cropping systems therefore requires integrated management approaches that combine balanced fertilization, enhanced-efficiency fertilizers, soil-test-based recommendations, precision nutrient management, and adoption of the 4R Nutrient Stewardship framework. Such interventions have consistently increased nitrogen recovery efficiency to 50–60% while maintaining or enhancing crop productivity and reducing environmental losses (Fixen, 2020; Zhang et al., 2015).



Enhanced-Efficiency Fertilizers as a Solution

Enhanced-efficiency fertilizers (EEFs) represent one of the most promising approaches for addressing Punjab's N paradox by synchronizing N release with crop demand and minimizing environmental losses. Unlike conventional urea, EEFs are designed to improve nitrogen recovery through controlled nutrient release or by inhibiting the biochemical processes responsible for nitrogen transformation and loss. Numerous studies have demonstrated that EEFs can increase NUE by 15–50%, reduce ammonia volatilization and nitrate leaching, and sustain crop yields without increasing fertilizer application rates (Azeem et al., 2014; Abalos et al., 2014). Their adoption is particularly relevant in the alkaline-calcareous soils of Punjab, where conventional urea often suffers substantial losses through volatilization and denitrification.

Urease Inhibitors

Urease inhibitors are compounds that temporarily suppress urease enzyme activity, thereby delaying the hydrolysis of urea and reducing ammonia volatilization losses. Among these, N-(n-butyl) thiophosphoric triamide (NBPT) is the most extensively studied and commercially successful inhibitor. By slowing the conversion of urea into ammonium carbonate, NBPT reduces the localized increase in soil pH responsible for ammonia formation (Cantarella et al., 2018).

Meta-analyses have reported reductions in ammonia volatilization ranging from 30 to 70%, accompanied by significant improvements in N recovery and grain yield (Silva et al., 2017; Cantarella et al., 2018). In wheat-rice systems, NBPT-treated urea has been shown to improve N uptake and increase NUE by 10–25% compared with conventional urea. The technology is particularly effective in alkaline soils, high-temperature environments, and situations where fertilizer incorporation or irrigation cannot be immediately performed (Zaman et al., 2013). Consequently, urease inhibitors offer a practical strategy for reducing N losses while maintaining farmer-friendly fertilizer management practices.

Polymer-Coated and Controlled-Release Urea

Polymer-coated urea (PCU) and other controlled-release fertilizers (CRFs) regulate nutrient release through semi-permeable coatings that gradually dissolve or diffuse N into the soil solution. This controlled release better matches crop N demand and reduces losses associated with excessive N concentrations in the soil during early growth stages (Trenkel, 2010).

Numerous field studies have demonstrated that polymer-coated fertilizers can increase N recovery efficiency by 20–40%, while simultaneously reducing nitrate leaching, ammonia volatilization, and nitrous oxide emissions (Li et al., 2021). Controlled-release fertilizers have shown particular promise in cereal production systems, where they can reduce the number of fertilizer applications while maintaining yields. In the context of Punjab, polymer-coated urea could be especially valuable for rice-wheat and maize-based systems where labor shortages and irrigation scheduling often limit timely split applications. However, high product costs remain a major barrier to widespread adoption, highlighting the need for targeted subsidy programs and local manufacturing initiatives.

Nitrification Inhibitors

Nitrification inhibitors delay the microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), thereby maintaining nitrogen in the less mobile ammonium form for a longer period. Common nitrification inhibitors include dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP), both of which suppress the activity of ammonia-oxidizing microorganisms in soil (Subbarao et al., 2006).

By slowing nitrification, these compounds reduce nitrate leaching and denitrification losses while increasing crop nitrogen uptake. Meta-analyses indicate that nitrification inhibitors can reduce nitrous oxide emissions by 30–50% and nitrate leaching by 20–40%, while increasing NUE and crop yields under suitable conditions (Abalos et al., 2014; Gilsanz et al., 2016). Their effectiveness is particularly relevant for irrigated rice systems and coarse-textured soils where nitrate losses are substantial. Integration of nitrification inhibitors with urease inhibitors may provide a synergistic approach for maximizing nitrogen retention in Punjab's agricultural soils.

Precision Nitrogen Management

Improving fertilizer efficiency requires not only advanced fertilizer products but also management strategies that ensure N is applied according to crop demand, soil conditions, and environmental factors. Precision nitrogen management technologies enable site-specific fertilizer recommendations that maximize productivity while minimizing environmental losses.

4R Nutrient Stewardship

The 4R Nutrient Stewardship framework advocates application of the right fertilizer source, at the right rate, at the right time, and in the right place. This science-based approach integrates agronomic, economic, and environmental considerations to optimize nutrient management (Fixen, 2020).

Implementation of 4R principles has consistently improved NUE across diverse cropping systems by enhancing synchronization between nitrogen supply and crop demand. Studies have reported increases in N recovery efficiency of 15–30% and substantial reductions in nutrient losses following adoption of 4R-based management strategies (Bruulsema et al., 2018). In Punjab, application timing and placement remain major challenges, as many farmers continue to apply large proportions of nitrogen at planting. Wider adoption of 4R practices could significantly improve fertilizer productivity without increasing input costs.

SPAD and Leaf Color Chart Technologies

Real-time crop sensing technologies offer an effective means of assessing plant N status and guiding fertilizer decisions. The Soil Plant Analysis Development (SPAD) chlorophyll meter and Leaf Color Chart (LCC) are among the most widely used tools for diagnosing N deficiencies during crop growth (Peng et al., 1996).

These technologies allow farmers to apply N only when crops exhibit actual demand, thereby avoiding excessive fertilizer applications. Research in rice and wheat systems has shown that SPAD- and LCC-based N management can reduce fertilizer consumption by 15–25% while maintaining or increasing grain yields and improving NUE (Ali et al., 2014; Islam et al., 2022). Their low cost and ease of use make them particularly attractive for smallholder farming systems in Pakistan.

GIS-Based Fertilizer Recommendations

Advances in geographic information systems (GIS), digital soil mapping, and geospatial analytics have transformed nutrient management from generalized recommendations to site-specific nutrient prescriptions. GIS-based approaches integrate soil fertility data, crop requirements, climate information, and management history to generate spatially explicit fertilizer recommendations (McBratney et al., 2005).

Punjab possesses one of the largest soil fertility databases in Pakistan, generated through decades of soil survey and testing programs. Integration of these databases with GIS technologies could facilitate the development of district-level and field-scale fertilizer recommendation maps, reducing both nutrient deficiencies and excessive fertilizer use. Site-specific nutrient management has been shown to increase NUE, reduce production costs, and improve environmental sustainability across diverse agricultural systems (Dobermann et al., 2004).

Nitrogen Management in Rainfed Agriculture

Rainfed agriculture occupies a substantial portion of the Pothohar Plateau and other semi-arid regions of Punjab, where rainfall variability strongly influences N dynamics and crop productivity. Unlike irrigated systems, nutrient availability in rainfed agriculture is closely linked to the timing, amount, and distribution of precipitation, making fertilizer management considerably more challenging (Farooq et al., 2017).

Traditional fertilizer schedules developed for irrigated agriculture often perform poorly under rainfed conditions because rainfall events may not coincide with crop nitrogen demand. Consequently, substantial nitrogen losses or periods of nutrient deficiency frequently occur. Rainfall-triggered nitrogen applications, whereby fertilizer is applied immediately before forecasted rainfall events, have shown considerable potential for improving fertilizer recovery and crop yields (Fageria and Baligar, 2005).

Conservation agriculture practices including minimum tillage, residue retention, and crop diversification further enhance NUE by improving soil structure, moisture conservation, and nutrient retention. Additionally, incorporation of organic amendments such as farmyard manure, compost, green manures, and biochar increases soil organic matter content, thereby enhancing water-holding capacity, microbial activity, and nutrient buffering (Lal, 2015). Integrated nutrient management approaches combining organic and inorganic nutrient sources are therefore particularly suitable for sustainable intensification of rainfed agriculture in Punjab.

Policy Dimensions of the Nitrogen Paradox

The persistence of Punjab's nitrogen paradox is influenced not only by agronomic factors but also by policy and institutional frameworks governing fertilizer production, distribution, and use. Pakistan allocates substantial financial resources to fertilizer support programs aimed at ensuring affordable access to urea and sustaining food production. While these policies have increased fertilizer availability, they have also unintentionally encouraged greater fertilizer consumption rather than greater fertilizer efficiency.

Input-oriented subsidy structures often fail to incentivize adoption of soil testing, precision nutrient management, or EEFs. Consequently, farmers frequently prioritize fertilizer quantity over fertilizer efficiency, perpetuating low NUE and environmental losses (Zhang et al., 2015). Redirecting a portion of fertilizer subsidy expenditures toward soil testing vouchers, digital advisory services, enhanced-efficiency fertilizers, and farmer training programs could generate substantially higher agronomic and environmental returns.

Public-private partnerships may play a critical role in accelerating adoption of innovative nutrient management technologies. Collaborative initiatives involving government agencies, fertilizer manufacturers, research institutions, and extension organizations could facilitate local production of controlled-release fertilizers, expansion of soil testing services, and dissemination of precision agriculture technologies. Furthermore, development of GIS-based nutrient recommendation platforms and mobile advisory applications could improve access to site-specific nutrient recommendations, particularly among smallholder farmers.

Ultimately, policy reforms should focus on shifting fertilizer management from an input-maximization paradigm toward an efficiency-maximization framework. Such a transition would improve farm profitability, reduce environmental degradation, and contribute significantly to sustainable agricultural intensification and national food security.

Future Research Priorities

Future research should focus on:

- Development of locally adapted enhanced-efficiency fertilizers.
- Integration of remote sensing and artificial intelligence for nitrogen management.
- Long-term assessment of soil health impacts.
- Nitrogen dynamics under climate change scenarios.
- Economic evaluation of subsidy reform options.
- Site-specific management strategies for rainfed systems.

Conclusion

Punjab's soil N paradox reflects a complex interaction between soil constraints, management practices, and policy frameworks. Despite high urea consumption, nitrogen recovery remains among the lowest in major agricultural production systems due to alkaline-calcareous soil conditions, low organic matter, and inefficient fertilizer management. Large N losses through volatilization, leaching, and denitrification not only reduce farm profitability but also threaten environmental sustainability. Adoption of EEFs, precision nutrient management tools, and 4R Nutrient Stewardship offers substantial opportunities to increase N recovery without increasing fertilizer inputs. Simultaneously, policy reforms that promote soil testing, digital nutrient management, and site-specific recommendations can accelerate the transition toward sustainable intensification. Improving nitrogen use efficiency will be essential for closing yield gaps, reducing environmental impacts, and ensuring long-term food security in Pakistan.

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