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Soil Fertility Constraints and Sustainability of Rice-Based Cropping Systems in India

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Abstract

Rice-based cropping systems are fundamental to food security and rural livelihoods in India, but their long-term sustainability is increasingly constrained by declining soil fertility, nutrient imbalance, and inefficient fertilizer use. Indian rice-growing regions exhibit considerable diversity in soil properties, agro-climatic conditions, and production environments, resulting in region-specific nutrient constraints. Continuous and intensive cultivation has contributed to nutrient depletion, particularly of nitrogen (N), phosphorus (P), and potassium (K), along with increasing deficiencies of secondary and micronutrients such as sulfur, zinc, iron, manganese, copper, and boron. Regional variations in rice productivity are closely associated with soil fertility status, water management, soil depth, drainage, acidity, salinity, and other soil-related constraints. In several rice-growing regions, low available N, P, or K is associated with low to medium productivity. Sustainable production therefore requires soil-test-based and site-specific nutrient management, balanced application of macro- and micronutrients, integration of organic and biological inputs, and adoption of conservation agricultural practices. Improving nutrient-use efficiency while maintaining soil health is essential for sustaining rice productivity and ensuring long-term food and resource security in India.

Keywords: Rice-based cropping systems; soil fertility; nutrient deficiency; nutrient management; rice productivity; soil health; sustainable agriculture

Introduction

Rice is a major food crop in India and plays a central role in national food security, rural livelihoods, and agricultural development. Rice-based systems, particularly rice–wheat systems, have contributed substantially to increasing food production and supporting millions of farming households. However, the sustainability of these systems is increasingly threatened by declining soil fertility, nutrient imbalance, intensive cultivation, and emerging environmental stresses.

Rice is cultivated under highly diverse agro-ecological conditions, covering a wide range of soil types and climatic environments. More than 15 major soil groups, including alluvial, red and yellow, black, and lateritic soils, support rice production across different regions of India. Rice is grown in 11 of the 15 agro-climatic zones of the country. Major rice ecosystems include irrigated wetlands, shallow rainfed lowlands, rainfed uplands, and deep-water rice environments, each having distinct soil, water, and nutrient-management constraints. Intensive cropping and imbalanced fertilizer application have accelerated nutrient depletion in several rice-growing areas. Deficiencies of N and

K are widespread, while deficiencies of secondary and micronutrients are also becoming increasingly important. Therefore, understanding regional soil fertility constraints and developing efficient nutrient-management strategies are essential for maintaining productivity, profitability, and soil health.

Methodology

This article was prepared as a review and synthesis of available information on soil fertility constraints and rice productivity in major rice-growing regions of India. Published literature, technical information, and documented soil-fertility observations were examined to identify major soil and nutrient constraints affecting rice-based cropping systems. The review considered soil nutrient status, rice productivity, nutrient deficiencies, physical and chemical soil constraints, fertilizer-management issues, and region-specific factors affecting rice production. Information on major rice-growing states and regions was synthesized to identify relationships between soil fertility conditions and rice productivity. Particular emphasis was given to deficiencies of N, P, K, sulfur, zinc, iron, manganese, copper, and boron, together with constraints such as soil acidity, salinity, poor drainage, erosion, shallow soil depth, crusting, and low water-holding capacity.

Results and Discussion

Diversity of rice-growing environments and soil fertility

Rice production in India occurs across highly diverse soil and climatic environments. Indian soils vary widely in texture, reaction, organic carbon content, and nutrient availability. Soil pH ranges from strongly acidic to alkaline conditions, while organic carbon and nutrient availability vary considerably among regions. More than half of the country's land area is affected by one or more soil-related constraints that can influence agricultural productivity. The major rice ecosystems differ in their production environments and nutrient requirements. Consequently, a uniform fertilizer recommendation is unlikely to provide optimum results across all rice-growing regions. Site-specific and soil-test-based nutrient management is therefore essential. These results are in conformity with earlier reported by Sharma et al. (2022), Patel et al. (2025) and Kumar et al. (2025), Brajendra et al. (2025) and Zoureen et al. (2025).

Nutrient depletion and emerging deficiencies

Continuous cultivation and inadequate nutrient replacement have resulted in nutrient mining in several intensive cropping systems. Nitrogen and potassium depletion are important concerns, while phosphorus deficiency is also widespread. Soil-test information indicates that a large proportion of Indian soils have low to medium N status, and substantial areas have low P availability. Deficiencies of sulfur and micronutrients, particularly zinc, iron, manganese, copper, and boron, are also increasingly recognized. Regional differences are particularly important. Iron deficiency has been reported in several states, while manganese deficiency is an important constraint in parts of the rice-wheat belt. Boron deficiency also varies considerably among regions, with particularly high occurrence reported in some eastern and lateritic soil regions. Such nutrient deficiencies can reduce crop growth, yield, nutrient-use efficiency, and ultimately the sustainability of rice-based production systems. These results are in conformity with earlier reported by Sharma et al. (2020), Sharma et al. (2022), Patel et al. (2025) and Kumar et al. (2025), Tuli et al. (2022) and Brajendra et al. (2025).

Regional soil fertility constraints and rice productivity

Rice productivity varies substantially among states and districts depending on soil fertility, water availability, climate, and management practices. In Andhra Pradesh, for example, some districts with low available P or K show relatively lower rice productivity, whereas areas with medium to high NPK status generally show higher productivity. Other important constraints include rapid permeability of red soils, drainage problems in clayey soils, zinc deficiency in several areas, potassium depletion in red soils, sulfide injury in some irrigated areas, crusting, and sub soil sodicity. Similar relationships occur in other rice-growing states. Low to medium NPK status is associated with relatively low or medium rice productivity in parts of Bihar, Himachal Pradesh, Karnataka, Nagaland, and Sikkim. In Himachal Pradesh, low available P, soil acidity, erosion, shallow soil depth, and low water-

Table 1: The major constraints identified from the reviewed information are summarized below.

Major constraint	Major implication for rice production	Management priority
Low N, P and K availability	Reduced crop growth and yield	Soil-test-based balanced fertilization
Micronutrient deficiencies	Reduced nutrient-use efficiency and crop performance	Zn, Fe, Mn, B and other nutrients based on soil/crop diagnosis
Soil acidity	Reduced availability of P, Ca, Mg and Mo; possible Al and Mn toxicity	Liming and balanced nutrient man agement where appropriate
Salinity/sodicity and poor drainage	Restricted root growth and nutrient uptake	Improved drainage and appropriate soil amendments
Low organic matter	Poor soil structure and nutrient-supplying capacity	Organic manures, residues and biological inputs
Erosion and shallow soil depth	Loss of fertile topsoil and low water storage	Conservation agriculture and erosion control

holding capacity are important constraints. In northeastern India, low availability of P and K, nutrient depletion, soil acidity, erosion, and micronutrient deficiencies affect rice production in several areas. These results are in conformity with earlier reported by Brajendra et al. (2016) Srilatha et al. (2019), Kale et al. (2021), Rathod et al. (2021), Parmar et al. (2022) and Patel et al. (2025).

Fertilizer management and environmental concerns

Imbalanced fertilizer application is an important constraint to sustainable rice production. Excessive application of nutrients can increase production costs and environmental risks, whereas inadequate application can restrict crop growth and yield. Nitrogen management is particularly important because both excessive and insufficient N application can reduce nutrient-use efficiency and affect environmental sustainability. The large variability in soil properties, climate, crop establishment methods, and cropping systems emphasizes the need for site-specific nutrient management. Integrated use of mineral fertilizers, organic amendments, crop residues, and biological inputs can improve nutrient availability and soil organic matter. Conservation practices such as reduced tillage, residue management, crop diversification, and efficient water management can further contribute to maintaining soil health. These results are in conformity with earlier reported by Brajendra et al. (2016) Bharamappanavara et al. (2020), Kale et al. (2021), Gorlapalli et al. (2022), Sahoo et al. (2022) and Gobinathet al. (2026).

Strategies for sustainable rice production

The sustainability of rice-based systems depends on maintaining soil fertility while improving nutrient-use efficiency. The major strategies include soil-test-based fertilizer recommendations, balanced application of macro-, secondary, and micronutrients, integrated nutrient management, recycling of crop residues, and incorporation of organic and biological inputs. Conservation agriculture practices, including reduced tillage, residue retention, crop diversification, and improved water management, can help conserve soil and water resources. Fertilizer recommendations should also be periodically updated according to changes in soil fertility, crop productivity, nutrient removal, and climatic conditions.

Conclusion

Rice-based cropping systems are essential for India's food security, but their long-term productivity is increasingly threatened by declining soil fertility, nutrient imbalance, and region-specific soil constraints. The reviewed information indicates that low or imbalanced availability of N, P, K, and micronutrients, together with acidity, salinity, poor drainage, erosion, shallow soil depth, and low organic matter, contributes to variations in rice productivity across regions. Sustainable rice production therefore requires a shift from generalized fertilizer recommendations towards soil-test-based, site-specific and balanced nutrient management. Integration of organic and biological inputs with mineral fertilizers, efficient water management, residue recycling, and conservation agriculture can improve soil health and nutrient-use efficiency. Regular monitoring of soil fertility and updating of fertilizer recommendations will be essential for maintaining productivity, profitability, and resilience of rice-based cropping systems under changing climatic conditions.

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