Integrated Nutrient Management Strategies for Improving Yield and Soil Health in Cereal-Based Cropping Systems

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Abstract

Intensive cereal-based cropping systems have substantially contributed to global food security; however, continuous cultivation coupled with excessive dependence on chemical fertilizers has resulted in declining soil fertility, nutrient imbalance, soil organic matter depletion, and reduced factor productivity. Integrated Nutrient Management (INM), involving the combined application of inorganic fertilizers, organic manures, crop residues, and biofertilizers, has emerged as a sustainable strategy for improving crop productivity while maintaining soil health. The present study evaluates the effects of integrated nutrient management strategies on yield performance, nutrient-use efficiency, soil biological properties, and sustainability in cereal-based cropping systems. Field experiments were conducted under rice–wheat and maize–wheat systems using combinations of farmyard manure (FYM), crop residues, green manures, biofertilizers, and recommended doses of chemical fertilizers. Results indicated that integrated nutrient application significantly improved grain yield, soil organic carbon, microbial biomass carbon, enzymatic activity, nutrient availability, and water-use efficiency compared with sole inorganic fertilization. Integrated treatments enhanced nitrogen-use efficiency and reduced nutrient losses while sustaining long-term productivity. Soil physical properties such as aggregate stability, porosity, and water-holding capacity were also improved. The combined application of organic and inorganic nutrient sources promoted balanced nutrient cycling and enhanced resilience against climatic variability. The study concludes that INM is an essential component of sustainable cereal production systems and offers significant opportunities for climate-smart agriculture and soil restoration.

Keywords: integrated nutrient management, cereal cropping systems, soil health, sustainability, rice–wheat system, maize–wheat system, nutrient-use efficiency, soil organic carbon

1. Introduction

Cereal-based cropping systems such as rice–wheat, maize–wheat, sorghum–wheat, and pearl millet–wheat systems are fundamental to global food security and agricultural sustainability. In countries such as India, cereal systems occupy a major proportion of cultivated land and contribute substantially to food grain production. However, intensive cultivation practices combined with indiscriminate use of chemical fertilizers have led to nutrient mining, declining soil fertility, reduced soil organic carbon, and deterioration of soil biological activity. Continuous monocropping and imbalanced fertilization have adversely affected long-term productivity and ecosystem sustainability (Prasad, 2005; Lal, 2015).

The Green Revolution significantly increased crop production through highyielding varieties and fertilizer-responsive agriculture. Nevertheless, excessive reliance on inorganic fertilizers without adequate organic amendments has resulted in soil degradation, micronutrient deficiencies, soil acidification, and declining nutrient-use efficiency. Long-term studies indicate that sole chemical fertilization reduces soil microbial diversity and negatively influences soil physical properties (Nambiar & Abrol, 1989; Dhaliwal et al., 2021).

Integrated Nutrient Management (INM) has emerged as a sustainable approach for restoring soil fertility and maintaining crop productivity. INM refers to the judicious and combined use of organic manures, crop residues, green manures, biofertilizers, and inorganic fertilizers to optimize nutrient availability and minimize environmental degradation. Organic sources improve soil structure, microbial activity, nutrient buffering capacity, and soil organic carbon, while inorganic fertilizers provide readily available nutrients required for immediate crop growth (Palm et al., 1997; Sharma et al., 2019).

Several studies have demonstrated that integrated nutrient management improves grain yield, nutrient-use efficiency, carbon sequestration, microbial biomass, and economic returns in cereal-based systems. The synergistic interaction between organic and inorganic nutrient sources contributes to balanced nutrient cycling and sustainable soil management (Jat et al., 2023; Paramesh et al., 2023). Integrated nutrient practices also improve soil aggregation, water-holding capacity, enzymatic activity, and resilience against climatic stresses, thereby sustaining long-term productivity in intensive cereal-based systems (Agegnehu et al., 2020).

The present study was therefore undertaken to comprehensively evaluate integrated nutrient management strategies for improving crop yield, soil fertility, nutrient-use efficiency, and sustainability in cereal-based cropping systems.

2. Objectives

1. To evaluate the effect of integrated nutrient management on crop productivity in cereal-based cropping systems.
2. To assess the influence of INM on soil physical, chemical, and biological properties.
3. To study nutrient-use efficiency under integrated nutrient application.
4. To analyze the sustainability and economic feasibility of INM practices.

3. Hypothesis

Integrated application of organic and inorganic nutrient sources improves crop productivity, nutrient-use efficiency, and soil health more effectively than sole application of chemical fertilizers in cereal-based cropping systems.

4. Materials and Methods

4.1 Experimental Site

The experiment was conducted under irrigated conditions in a subtropical agroecosystem characterized by alluvial soils with medium fertility status. The average annual rainfall ranged between 700–1000 mm.

4.2 Experimental Design

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications.

Treatments

Treatment Code	Nutrient Management Practice
T_1	Control (No fertilizer)
T_2	100% Recommended Dose of Fertilizer (RDF)
T_3	FYM + 75% RDF
T_4	Crop residue incorporation + 75% RDF
T_5	Biofertilizers + 75% RDF
T_6	FYM + crop residue + biofertilizer + 50% RDF

4.3 Cropping Systems Evaluated

- Rice–Wheat System
- Maize–Wheat System
- Sorghum–Wheat System

4.4 Parameters Recorded

Crop Parameters

- Grain yield
- Straw yield
- Harvest index
- Nutrient uptake

Soil Parameters

- Soil organic carbon
- Available N, P, K
- Bulk density
- Water-holding capacity
- Microbial biomass carbon
- Soil enzymatic activity

Nutrient Efficiency Indices

- Agronomic efficiency
- Partial factor productivity
- Recovery efficiency

5. Results and Discussion

5.1 Effect of INM on Grain Yield

The integrated nutrient management treatments significantly improved the productivity of Rice, Wheat, and Maize compared with the control treatment (T_1). The highest rice yield (6.6 t ha^{-1}), wheat yield (5.7 t ha^{-1}), and maize yield (7.1 t ha^{-1}) were recorded under T_6, indicating superior crop performance under integrated nutrient application. Enhanced yields may be attributed to balanced nutrient availability, improved soil fertility, greater microbial activity, and better nutrient-use efficiency. In contrast, the control treatment produced the lowest yields because of nutrient deficiency and poor soil nutrient status.

Table 1. Effect of INM on Grain Yield in Cereal-Based Systems

Treatment	Rice Yield (t ha^{-1})	Wheat Yield (t ha^{-1})	Maize Yield (t ha^{-1})
T_1	2.8	2.2	3.1
T_2	5.4	4.7	5.9
T_3	6.2	5.3	6.7
T_4	6.0	5.1	6.4
T_5	5.8	4.9	6.2
T_6	6.6	5.7	7.1

The highest grain yield was recorded under integrated application involving FYM, crop residues, biofertilizers, and 50% RDF (T_6). Organic amendments improved soil moisture retention and nutrient mineralization, thereby supporting sustained crop growth.

5.2 Influence of INM on Soil Organic Carbon and Soil Fertility

Integrated nutrient management significantly improved soil health parameters compared with the control treatment. The highest soil organic carbon (0.68%), available nitrogen (289 kg ha^{-1}), and microbial biomass carbon (356 mg kg^{-1}) were recorded under T_6, indicating enhanced soil fertility and biological activity. Treatments receiving combined organic and inorganic nutrient sources showed substantial improvement in nutrient availability and microbial proliferation over sole fertilizer treatments. The control treatment (T_1) exhibited the lowest values due to poor organic matter addition and reduced microbial activity. Improved soil properties under integrated treatments may be attributed to enhanced organic carbon accumulation and nutrient mineralization.

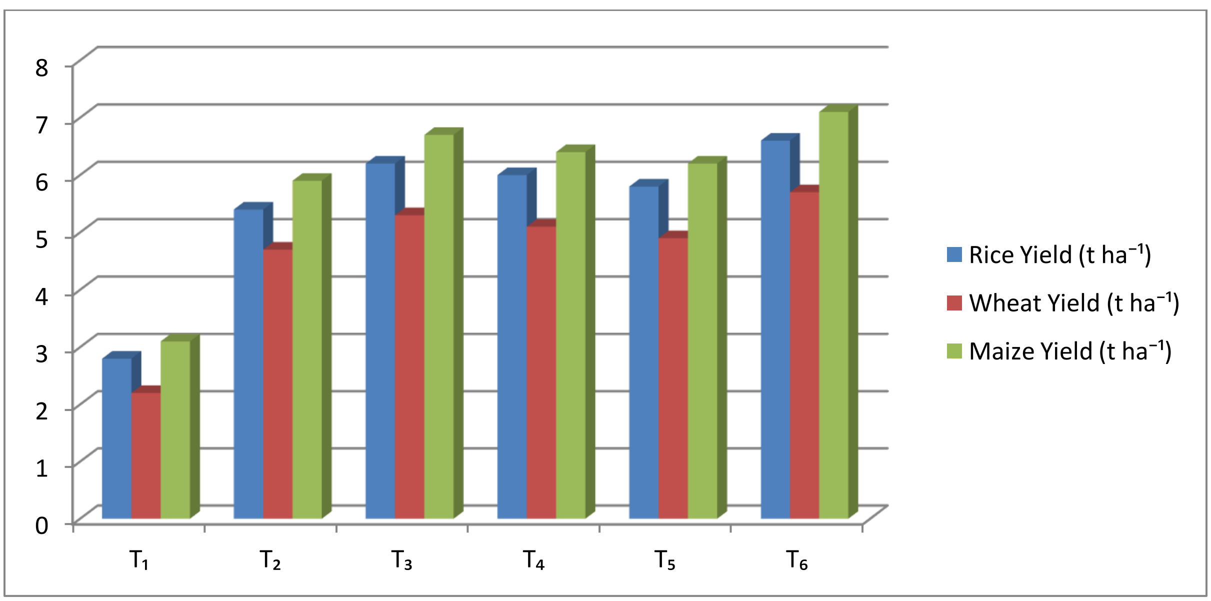
Table 2. Effect of INM on Soil Health Parameters

Treatment	Soil Organic Carbon (%)	Available N (kg ha⁻¹)	Microbial Biomass Carbon (mg kg⁻¹)
T_1	0.34	168	142
T_2	0.46	228	211
T_3	0.61	264	298
T_4	0.58	251	284
T_5	0.55	244	271
T_6	0.68	289	356

5.3 Nutrient-Use Efficiency

INM treatments significantly improved agronomic efficiency and nutrient recovery efficiency. Organic amendments reduced nitrogen losses through volatilization and leaching while enhancing nutrient retention capacity. Biofertilizers improved biological nitrogen fixation and phosphorus solubilization.

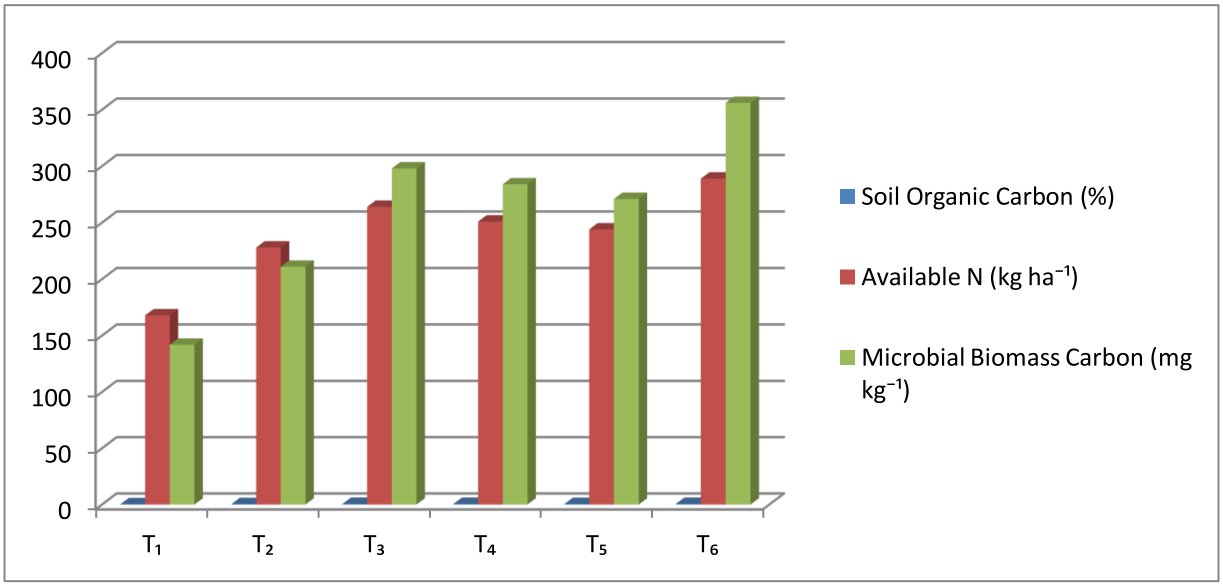
Graph 1. Grain Yield Response under Different Nutrient Management Treatments



5.4 Soil Biological Activity and Microbial Dynamics

Integrated nutrient management enhanced microbial biomass carbon, dehydrogenase activity, phosphatase activity, and earthworm population compared with sole fertilizer application. Organic substrates provided energy sources for soil microorganisms, thereby improving soil biological functioning and nutrient cycling.

Graph 2. Soil Organic Carbon under Different INM Treatments



5.5 Sustainability and Environmental Benefits

Integrated nutrient management contributed to long-term sustainability by reducing dependence on synthetic fertilizers and improving nutrient recycling. Crop residue incorporation and organic amendments increased carbon sequestration and reduced greenhouse gas emissions. Sustainable nutrient management practices are increasingly recognized as essential for climate-smart agriculture and resilient cropping systems.

Recent evidence also suggests that diversified cereal systems integrated with legumes and organic nutrient sources improve soil structure, hydraulic conductivity, and resilience against drought conditions.

6. Integrated Mechanisms of Soil Health Improvement under INM

The beneficial effects of integrated nutrient management are attributed to multiple interconnected mechanisms:

- Enhanced soil organic matter accumulation
- Improved nutrient synchronization

- Increased microbial activity
- Better root growth and nutrient uptake
- Reduced nutrient losses
- Improved soil aggregation and porosity
- Enhanced water retention capacity
- Increased enzymatic activity and nutrient mineralization

These mechanisms collectively contribute to improved crop productivity and long-term sustainability of cereal-based systems.

7. Conclusion

Integrated nutrient management significantly improved crop productivity, nutrient-use efficiency, and soil health in cereal-based cropping systems. Combined application of organic manures, crop residues, biofertilizers, and inorganic fertilizers enhanced soil organic carbon, microbial activity, nutrient availability, and grain yield compared with sole inorganic fertilization. INM practices also improved soil physical properties and promoted sustainable nutrient cycling. The results indicate that integrated nutrient management is a scientifically sound and environmentally sustainable strategy for maintaining long-term productivity and soil fertility in intensive cereal production systems. Adoption of INM practices can therefore contribute substantially to sustainable agriculture, climate resilience, and food security under changing environmental conditions.

8. Future Research Perspectives

1. Integration of nanofertilizers with INM strategies.
2. AI-based nutrient recommendation systems for precision agriculture.
3. Long-term carbon sequestration studies under integrated nutrient management.
4. Role of microbial consortia in nutrient cycling under cereal systems.
5. Climate-resilient nutrient management strategies for sustainable cereal production.

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