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Integrated nutrient management for sustainable wheat production: Effects on soil health, productivity and nutrient use efficiency

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Abstract
Wheat-based cropping systems, especially the rice-wheat production system of the Indo-Gangetic Plains, are essential for maintaining food production and addressing the nutritional needs of an increasing population. Due to its importance, long term intensive cultivation has led to several problems such as depletion of soil organic matter, nutrient imbalance, declining biological activity and excessive dependence on chemical fertilizers. These practices result in reduced nutrient use efficiency as well as cause environmental problems such as nutrient leaching and increased greenhouse gases emissions. The problems also emphasize the need for sustainable nutrient management techniques to maintain production while ensuring soil and environmental health. Integrated Nutrient Management (INM) involves a combined use of mineral fertilizers with organic amendments and biological components to supply nutrients. Addition of organic resources is beneficial to the physical condition of the soil through improvement of soil structure, water holding capacity and root growth. Moreover, the enhanced microbial activity increases the efficiency of providing crops with nutrients through stimulating the transformation and recycling of nutrients. INM enhances nutrient synchronization and minimizes nutrient losses leading to improved nutrient use efficiency, stable wheat yields and sustainability of wheat-based production systems in long run.

Keywords: Integrated nutrient management, wheat, soil fertility, soil organic carbon, nutrient cycling, nutrient use efficiency, rice–wheat system, sustainability

Introduction
Wheat is among the major cereal crops and play a significant role in global food security, especially in South Asia and in the region of Indo-Gangetic plains of India. Various wheat-based cropping systems such as rice–wheat rotations have contributed significantly to food production; however, continuous intensive cultivation and imbalanced fertilizer use have led to soil degradation and nutrient imbalance, ultimately affecting long-term crop productivity (Ladha *et al*., 2003; Manna *et al*., 2007).

Dependence on only the synthetic fertilizers has led to deterioration of soil fertility and dynamics and, thus, reduced long-term sustainability of wheat-based cropping systems (Singh, 2018) [34]. Sustainable nutrient management approaches are, therefore, crucial to ensuring proper maintaining and improving of soil fertility and stabilization of wheat crop productivity.

INM is an emerging concept to achieve higher soil fertility and grain yields through the combined application of various sources of plant nutrients, including chemical fertilizers, organic manure, crop residues, compost and biofertilizers. INM improves soil fertility and nutrient cycling through integrated nutrient sources. Long-term positive effects of INM are the increase in soil organic carbon, microbial community, nutrient recovery and stability of yield in wheat-based production system (Roy *et al.*, 2006; Manna *et al*., 2007).

Recent studies have highlighted the importance of INM in improving sustainable agriculture, minimizing nutrient losses and increasing climate change resilience in wheat production (Singh *et al*., 2023; Kaur *et al*., 2023; Ranjan *et al*., 2023). Thus, it is important to understand the significance of INM under climate change conditions for sustainable wheat production.

Graphical Framework / Conceptual Overview
INM for wheat based cropping systems are applied with chemical fertilizers, organic manures, crop residues, composts, vermicompost and bio-fertilizers. Use of combination of different nutrient sources can ensure good soil fertility and sustainable production of crop. Organic amendments can improve the physical conditions of soil such as water holding capacity, and nutrient availability, while biofertilizers can help enhance biological processes for nutrient transformation. Combined application of the various sources of nutrients can ensure nutrient cycling, improve the soil structure, roots grow better in the soil. Thus, crop utilize the available nutrients more effectively with lesser amount of fertilizer loss and sustainable wheat production. It also helps in the environment protection by utilizing the resource use more effectively and less adverse effects by chemical fertilizer use alone (Lal, 2004; Singh *et al*., 2023; Meena and Suthar, 2022) [24, 28, 35].

Objectives
1. To investigate the influence of INM practices on wheat growth, yield performance, and related yield attributes.
2. To evaluate the changes in soil physical, chemical, and biological characteristics under different INM approaches.

3. To examine the role of INM in improving nutrient uptake and nutrient use efficiency.
4. To evaluate the contribution of INM towards environmental sustainability in wheat-based systems.

Major Components of INM in Wheat

Success of INM depends on the efficient integration of inorganic fertilizers with locally available organic and biological sources of nutrients (Roy *et al*., 2006; Bhardwaj *et al*., 2014).

1. Chemical Fertilizers

Commercial mineral fertilizers provide readily available nitrogen, phosphorus, and potassium required for wheat growth; however, prolonged excessive fertilizer application may also lead to increase soil acidification, micronutrient imbalance, and nutrient mining under intensive cereal systems, and their long-term use alone results in nutrient imbalance, Soil depletion, reduced microbial activity and deterioration of soil structure under intensive cereal-based cropping systems (Manna *et al*., 2007) [26].

2. Farmyard Manure (FYM)

FYM is one of the major organic nutrient sources in wheat-based production systems. Its inclusion in INM practices provides greater benefits for soil quality and nutrient retention than the sole application of inorganic fertilizers. FYM improves soil functioning as a slow-release nutrient source improving soil fertility and supporting better nutrient retention and microbial activity (Manna *et al.,* 2007; Bajpai *et al*., 2006) [4, 26]. Recent scientific evidence suggests that improved nutrient retention and microbial activity under long-term FYM integrated treatments in wheat-based cropping systems (Dhaliwal *et al*., 2021; *ICAR-IISS,* 2021) [11].

3. Compost and Vermicompost

Compost and vermicompost increases fertility of the soil by making the available nutrients in slow releasing forms along with promoting biological activity. This is because the integration of vermicompost and mineral fertilizer has been proved to promote root growth and biological activities, hence increasing the efficiency of nutrients and their availability (Arancon *et al*., 2004; Edwards *et al*., 2011) [3, 12].

4. Crop Residues

Crop residue recycling is an important INM practice for wheat-based farming systems, and compared with residue removal and burning, residue incorporation, nutrient retention, soil moisture conservation, and temperature regulation, thereby decreasing adverse environmental impacts associated with residue burning and improving long-term soil fertility and yield stability under rice–wheat systems and conservation agriculture practices such as Happy Seeder further improve residue recycling and soil moisture conservation in rice–wheat systems (Bhattacharyya *et al*., 2015; Jat *et al.,* 2020; Sarkar *et al*., 2020) [8, 19, 33].

5. Green Manuring

Green manuring is the process of growing leguminous crops and incorporating them into the soil environment through organic matter incorporation and natural nitrogen fixation processes and green manuring improves sustainability of intensive wheat-based cropping systems by enhancing biological nitrogen fixation, microbial activity and soil structure as compared to fertilizer alone while long-term addition of green manure together with fertilizers and wheat productivity and Sesbania green manuring contributes about 40–60 kg N ha^{-1} through biological nitrogen fixation (Manna *et al.,* 2007) [26].

6. Biofertilizers

Biofertilizers such as Azotobacter, Azospirillum, phosphate solubilizing microorganisms, and arbuscular mycorrhizae play a vital role in providing nutrients through increased nutrient mobilization, increased phosphorus solubility, and root development. They help in promoting microflora in the soil, increasing tolerance against environmental stresses, and enhancing nutrient absorption in wheat plants. Unlike the application of only chemical fertilizers, the use of biofertilizers helps in facilitating nutrient transformations and reducing reliance on artificial fertilizers. But their performance is contingent on conditions like moisture and temperature (Bhardwaj *et al.,* 2014[7]; Bashan, 2004).

Economic Importance of INM in Wheat

INM helps in achieving better economic gains through the stabilization of wheat productivity and minimization the application of chemical fertilizer. Several studies have reported that the partial replacement of fertilizers using FYM and compost can help achieve stable yields, while maximizing economic benefits due to lower levels of fertilization. INM further ensures recovery of soil fertility and reduces future fertilizer demand. However, economic sustainability is influenced by labor supply, transport costs, and the availability of organic materials. The mechanized removal of crop residue, coupled with decentralized composting, will enhance adoption and profitability (Bajpai *et al*., 2006) [4]. INM contribute to lower production expenses by promoting the utilization of on-farm organic resources and the recycling of crop residues, thereby improving long-term economic stability in wheat-based systems. (Roy *et al*., 2006; Jat *et al*., 2022; Tandon, 2007) [20, 31, 36].

Benefits of Integrated Nutrient Management

INM offers several agronomic, economic and environmental benefits in wheat based cropping systems. Integrated use of organic and inorganic nutrient sources improves soil fertility, maintains nutrient balance and enhances long-term wheat productivity compared to sole fertilizer application (Roy *et al*., 2006; Manna *et al.*, 2007) [26, 31].

INM improves soil aggregation, pore space and water-holding capacity leading to better root development and moisture conservation, and organic inputs enhance nutrient mineralization and improve soil carbon status (Lal, 2004; Goyal *et al.*, 1992) [16, 24].

INM ensures a balanced and timely supply of nutrients according to crop requirements, thereby minimizing nutrient losses caused by leaching, volatilization, and nutrient fixation while biofertilizers enhance biological nitrogen fixation and phosphorus solubilization, resulting in improved nutrient uptake and lower dependence on chemical fertilizers (Cassman *et al*., 2002; Bhardwaj *et al*., 2014) [7, 10].

INM also contributes to environmental sustainability through carbon sequestration, reduced residue burning and lower greenhouse gas emissions in intensive rice–wheat systems, thereby improving resilience and stability of wheat-based cropping systems under long-term conditions (Meena and Suthar, 2022; Ranjan *et al.*, 2023; Jat *et al*., 2022) [28, 30].

Wheat-Based Cropping Systems

Various cropping patterns have developed for growing wheat in South Asia, particularly in the Indo-Gangetic Plains of India. Among these, the rice-wheat cropping pattern is the most common and plays a vital role in ensuring food security (Ladha *et al.*, 2003) [23]. Other significant wheat-based cropping patterns include maize-wheat, soybean-wheat, cotton-wheat, pearl millet-wheat, and pulse-wheat. Nutrient dynamics and sustainability vary among these systems. Rice-wheat systems are more intensive, often depleting soil organic carbon and leading to nutrient loss and residue management challenges due to continuous cereal cropping.

In contrast, incorporating pulses enhances biological nitrogen fixation and soil fertility, while maize-wheat systems help maintain nutrient balance and crop diversity. The presence of legumes boosts the organic matter in the soil and improves nutrient availability. Integrated nutrient management is crucial for sustaining productivity across different wheat-based cropping systems. Additionally, conservation agriculture practices further improve system sustainability through better residue management and soil health (Manna *et al.*, 2007) [26]. Soil degradation is speeding up due to the intensive cultivation of crops and the removal of crop residue.

Recent research on conservation agriculture-based wheat systems shows that adopting integrated nutrient management practices can boost sustainable agricultural practices (Jat *et al*., 2022; Kaur *et al*., 2023). Many studies were conducted, and it has been demonstrated by numerous scientific studies that the use of fertilizer with FYM, biofertilizer, and crop residues plays a vital role in enhancing soil fertility and stability of production in the rice-wheat system (Bhattacharyya *et al*., 2015; Ranjan *et al*., 2023).

Table 1: Major Wheat-Based Cropping Systems in India and role of INM

Cropping system	Major production constraint	Role of integrated nutrient management (INM)	Supporting references
Rice–Wheat	Soil depletion, residue burning, nutrient mining	Enhances residue recycling, SOC and yield stability	Ladha *et al.* (2003); Manna *et al*. (2007); Bhattacharyya *et al*. (2015) [8, 23, 26]
Maize–Wheat	Nutrient imbalance and declining soil fertility	improves nutrient balance and recovery efficiency	Roy *et al.* (2006); Jat *et al*. (2022) [20, 31]
Pulse–Wheat	Low residual nutrient availability	Biological nitrogen fixation and improvement in soil fertility	Bhardwaj *et al.* (2014); Roy *et al*. (2006) [7, 31]
Soybean–Wheat	Declining soil organic matter	Enhances nutrient cycling and SOC	Manna *et al*. (2007); Kaur *et al*. (2023) [22, 26]
Cotton–Wheat	Soil degradationand micronutrientdeficiency	Improves nutrient availability and soil biological activity	ICAR-IISS (2021); Dhaliwal *et al*. (2021) [11]

Note: INM = Integrated Nutrient Management; SOC = Soil Organic Carbon.

Effect of INM on Wheat Yield and Yield Attributes

INM significantly increases wheat yield and yield attributes compared to sole fertilizer application due to improved soil health and nutrient availability, and long-term rice–wheat system studies indicate that yield remains stable initially under fertilizers alone but declines in later stages due to SOC depletion and nutrient imbalance. Nevertheless, integration of FYM, compost and crop residues with recommended fertilizer doses improves yield stability and long-term sustainability (Manna *et al.*, 2007; Bajpai *et al*., 2006) [4, 26].

INM leads to yield improvements characterized by better yield components such as increased tillering, longer spikes, more grains per spike, and higher thousand-grain weight. The organic matter improves nutrient synchronization and reduces losses, thereby enhancing tillering, grain filling, harvest index and yield stability, and long-term experiments report approximately 8–25% increase in wheat productivity under INM practices (Singh *et al.*, 2023) [35]. A major approach to improving wheat yield in late sown crops due to shorter growth period and poor uptake of nutrients is nutrient prescription method (Meena *et al.*, 2023) [27].

Recent studies also indicate improved nutrient uptake and grain filling under integrated nutrient application, although further long-term research is crucial to assess carbon sequestration, greenhouse gas emissions and climate resilience in diversified wheat systems (Kumar *et al*., 2023; Lodhi *et al.*, 2024) [25, 30]. Further long-term experiments are still required to evaluate carbon sequestration, greenhouse gas emissions, and climate resilience in diversified wheat systems (Singh *et al*., 2024; Kaur *et al*., 2024) [25].

Table 2: Yield Response of Wheat to Different INM Practices

Nutrient management practice	Yield response (typical trend)	Major agronomic effect	Supporting references
Control (no nutrient input)	Very low yield	Severe nutrient deficiency and poor soil fertility	Ladha *et al*. (2003) [23]
100% RDF (NPK only)	Moderate yield; stagnation risk long-term	Nutrient imbalance and SOC depletion under continuous use	Manna *et al*. (2007); Ladha *et al.* (2003) [23, 26]
RDF + FYM	Higher yield (+10–25%) and stable	Improved nutrient availability and soil fertility	Manna *et al*. (2007); Bajpai *et al.* (2006) [4, 26]
75% RDF + FYM	Comparable yield with improved soil fertility	Reduced fertilizer dependence and improved soil health	Bajpai *et al*. (2006) [4]
RDF + compost/vermicompost	Improved yield and nutrient uptake	Enhanced microbial activity and nutrient mineralization	Arancon *et al*. (2004); Edwards *et al.* (2011) [3, 12]

RDF + residues	Higher yield stability and improved SOC	Improved moisture conservation and nutrient recycling	Bhattacharyya *et al*. (2015); Ranjan *et al*. (2023) [8, 30]
RDF + biofertilizers	Moderate yield gain; improved NUE	Enhanced biological nitrogen fixation and nutrient uptake	Bhardwaj *et al*. (2014) [7]; Bashan *et al*. (2004)

Note: RDF = Recommended Dose of Fertilizers; FYM = Farmyard Manure; SOC = Soil Organic Carbon; NUE = Nutrient Use Efficiency.

Effect of INM on Soil Physical Properties

Soil parameters like bulk density, porosity, infiltration, and aggregate stability are important for wheat growth and nutrient use. They are crucial for the development of wheat roots, the movement of water through the soil, and the availability of nutrients during wheat farming. Using inorganic fertilizers without organic matter can lead to soil compaction, loss of aggregate stability, poor aeration, and low infiltration rates. Integrated Nutrient Management (INM) improves soil quality by providing organic matter, which binds soil particles and helps form aggregates (Lal, 2004; Bhattacharyya *et al.*, 2015) [8, 24]. Adding farmyard manure (FYM) and compost encourages microbial production of polysaccharides. This boosts soil biological quality, leading to better soil aggregation, lower bulk density, and higher porosity, which aid root growth and water availability. Incorporating crop residues enhances surface cover, reduces water loss from evaporation, and increases soil moisture, especially in wheat farming in semi-arid areas (Sarkar *et al.*, 2003; Naresh *et al.*, 2017) [29, 32]. Long-term INM practices help maintain a favorable soil structure in intensive cereal systems. In addition to improving the physical properties of soil, INM also affects soil fertility and nutrient behavior (ICAR, 2023; Bhattacharyya *et al.*, 2012) [9, 17].

Table 3: Effect of INM on Soil Physical properties in wheat-based systems

Soil physical Indicator	Fertilizer only	INM (Organic + fertilizer)	Major improvement under INM	Key references
Bulk density	Higher	Lower	Reduced soil compaction and better root growth	Lal (2004); Manna *et al*. (2007) [24, 26]
Aggregate stability	Lower	Higher	Improved soil aggregation and structure	Bhattacharyya *et al.* (2015); Manna *et al*. (2007) [8, 26]
Infiltration rate	Low–moderate	Improved	Better water movement and aeration	Sarkar *et al.* (2003) [32]
Water holding capacity	Lower	Higher	Improved moisture retention under wheat cultivation	Sharma *et al*. (2000)
Soil porosity	Lower	Higher	Enhanced root proliferation and gas exchange	Bhattacharyya *et al*. (2015) [8]

Effect of INM on Soil Chemical Properties

1. Soil Organic Carbon (SOC)

SOC is not only strongly indicative of the short-term nutrient status of soil but also a core theme for sustainable long–term land use management. Enhancing soil structure, nutrient availability, soil biology and moisture retention capacity of soils. The SOC buildup is almost negligible under fertilizer-only regime, whereas, considerable SOC can build up under INM due to the continuous addition of organic carbon from FYM, compost and straw residue. Higher SOC is useful in improving aforementioned soil and nutrient use efficiency. Thus, it assists in sustaining nutrient supply and wheat grains yield stability at cropping system level of crops being preceded with wheat (Manna *et al*., 2007; Lal, 2004) [24, 26]. The recent experiments on alarming rice-wheat cropping systems have reported the positive contributions of organic amendments combined with chemical fertilizers on SOC fractions (Ghosh *et al*., 2025; Kaur *et al*., 2023; Ranjan *et al*., 2023) [15, 22]. Many studies on fertilizer applications in Indian agriculture always indicate the improvement of SOC fractions and nutrient buffer capacity by dependence on INM (AICRP-LTFE, 2022; ICAR-IISS, 2021). Latest studies conducted in India showed that using FYM, crop residues, and fertilizers helps improve carbon sequestration, microbial activity, and the stability of SOM in intensive wheat-based cropping systems (Dhaliwal *et al*., 2021) [11]. It also aids in carbon sequestration and soil aggregation, which provides the soil with resilience against different adverse climatic conditions (Singh *et al*., 2024) [25].

2. Availability of Macronutrients (N, P and K)

INM strategy helps in improving the availability and balanced supply of important elements like nitrogen, phosphorous, and potassium within the wheat production system. The utilization of organic sources along with inorganic fertilizers results in more effective mineralization of nutrients, their efficient retention, and timely availability as per the requirements of crops. The timely availability minimizes the losses due to leaching and volatilization and ensures improved absorption efficiencies. Organic acid produced during the process enhances the solubility of phosphorus while recycled residue is helpful for potassium replenishment. (Cassman *et al*., 2002; Roy *et al*., 2006; Manna *et al*., 2007; Kaur *et al*., 2023) [10, 22, 26, 31].

3. Micronutrient Availability

Micronutrient deficiency diseases increase in wheat cultivation systems; notably the deficiencies of Zinc and Sulphur (S). The deficiency in Zinc negatively affects wheat grain quality in terms of tillering, grain development and nutritional value, whereas the deficiency of Sulphur is becoming prevalent due to the continuous application of high analysis fertilizers which do not contain Sulphur. Prolonged cereal cultivation along with insufficient fertilizer application would lead to micronutrient deficiency diseases in wheat systems. INM helps to increase micronutrient bioavailability by virtue of increased microbial action, breakdown of organic matter, chelation reactions, and cycling of nutrients. Organic inputs enhance micronutrient solubility and prevent nutrient immobilization, thus making it possible to obtain higher nutrient availability in wheat crops. Nevertheless, severe cases of micronutrient deficiencies will need specific micronutrient fertilization along with integrated nutrient management practices for sustaining wheat productivity and grain quality (Alloway, 2008) [2].

Table 4: Effect of INM on Soil Chemical Indicators

Soil chemical indicator	Fertilizer only	INM-based management	Key references
SOC	Low/marginal increase	Significant increase	Lal (2004); Meena and Suthar (2022) [24, 28]
Available N	Moderate; loss prone	Higher; synchronized supply	Cassman *et al.* (2002) [10]
Available P	Limited due to fixation	Improved due to organic acids	Roy *et al.* (2006) [31]
Available K	Declines long-term	Maintained/improved	Roy *et al.* (2006) [31]
Zn and S availability	Deficiency common	Improved	Alloway (2008) [2]; ICAR-IISS (2021)

Effect of INM on Soil Biological Properties

Soil biological properties including microbial biomass, microbial enzyme activity, and microbial diversity have an effect on nutrient mineralization and soil fertility. INM increases biological aspects of soil through the utilization of organic manure that promotes microbial growth and nutrient transformations during the wheat growing process. Some research works have indicated that the amendment of organic manure along with fertilizers increases the level of microbial biomass carbon and enzyme activity like dehydrogenase, urease, and phosphatases enzymes when compared with fertilizers alone (Goyal *et al*., 1992; Manna *et al.*, 2007) [16, 26]. Application of biofertilizers increases nitrogen availability, wheat growth, and nutrient uptake efficiency in wheat-based farming practices. Biofertilizers increase the soil's nitrogen fixation capabilities through the supply of nitrogen fixing microorganism and phosphate solubilizing microbes to the soil. However, biofertilizers cannot be applied effectively due to variations in soil and biofertilizer qualities (Bhardwaj *et al*., 2014) [7]. Recent studies indicated increased microbial diversity and enzyme activities under INM practices (Francioli *et al*., 2016) [14].

Table 5: Soil Biological Response under INM

Biological parameter	Fertilizer only	INM	Major biological response	Supporting references
Microbial biomass carbon	Lower	Higher	Increased microbial population and activity	Manna *et al*. (2007); Goyal *et al.* (1992) [16, 26]
Enzyme activity	Lower	Higher	Enhanced nutrient transformation processes	Goyal *et al.* (1992) [16]
Nutrient mineralization	Moderate	Higher	Improved nutrient release from organic matter	Manna *et al*. (2007); Goyal *et al.* (1992) [16, 26]
Microbial diversity	Lower	Improved	Better rhizosphere functioning and soil ecology	Kumar *et al*. (2022); Patel *et al*. (2024) [25]
Root–microbe interaction	Limited	Enhanced	Improved nutrient uptake and stress tolerance	Bashan *et al*. (2004); Bhardwaj *et al.* (2014) [7]

Effect of INM on Nutrient Uptake and Nutrient Use Efficiency (NUE)

1. Concept of Nutrient Use Efficiency

NUE refers to the ability of wheat plants to absorb, utilize, and convert applied nutrients into economic yield. In intensive wheat cultivation, it is often reduced due to significant nutrient losses occurring through leaching, volatilization, denitrification, and fixation processes. Imbalanced fertilizer application result in poor nutrient recovery rate and environmental degradation. INM enhances NUE through synchronizing of nutrient release from organic and inorganic sources with crop demand, thereby improving nutrient retention, nutrient uptake, and fertilizer use efficiency (Cassman *et al*., 2002; Jat *et al*., 2022; Singh *et al*., 2023) [10, 20, 35].

2. Mechanisms of NUE Improvement under INM

INM enhances the NUE process through integrated physical, chemical, and biological means. Organic matter releases nutrients and boosts both SOC as well as the CEC (cation exchange capacity) of soils, also their buffering properties called nutrient loss. Phytomass storage of nutrients in the organic matter mineralization is well intertwined with needs at plant level. Biofertilizers enhance nitrogen fixation and phosphate solubilization. The improved capacity will contribute to enhanced root growth, nutrient uptake and grain yield of wheat (Lal, 2004; Cassman *et al*., 2002; Roy *et al.*, 2006) [10, 24, 31]. INM has also been reported for synchronizing nutrient release promoting NUE in wheat irrigation (Singh *et al*., 2023; Bhardwaj *et al*., 2023; Meena *et al.*, 2023) [6, 27, 35]. Recent studies on wheat emphasized that nearer synchronization of nutrient supply to nutrient demand in the INM system caused an increase of efficiency of applied nutrients and subsequently wheat productivity (Kaur *et al.*, 2023; Ghosh *et al.*, 2025) [15, 22].

Table 6: Effect of INM on Nutrient Uptake and Nutrient Use Efficiency (NUE)

Parameter	Fertilizer only	INM	Major effect on wheat production	Key references
Nitrogen uptake	Moderate	Higher	Better nitrogen recovery and crop growth	Cassman *et al.* (2002) [10]
Phosphorus uptake	Moderate	Improved	Reduced phosphorus fixation and better uptake	Roy *et al*. (2006) [31]
Potassium uptake	Declining trend	Maintained or improved	Better nutrient balance and crop performance	Roy *et al*. (2006) [31]
Nutrient losses	Higher	Reduced	Lower leaching and volatilization losses	Lal (2004) [24]
NUE (overall)	Low–moderate	Higher and stable	Improved synchronization of nutrient release and crop demand	Singh *et al*. (2023); Meena *et al*. (2023); Kaur *et al.* (2023) [22, 27, 35]

Role of INM in Rice–Wheat Cropping System Sustainability

Rice–wheat cropping system Rice–wheat cropping system (RWCS) is the most dominant cereal-based cropping system in South Asia, particularly in the Indo-Gangetic plains which has a major portion for food security. However, higher mechanization and chemical fertilizers have caused a decrease in the soil organic matter, nutrients, reduced microbial activity and productivity (Ladha *et al*., 2003) [23]. It has been shown that fertilizer-based systems are capable of generating yields over short periods. But permanent productivity is conditioned to integration of organic residues in the system (Manna *et al*, 2007) [26]. INM increases SOC pools, sustain productivity and recycling of residue for long time. Mixing mineral fertilizers with crop residues helps to sustain soil buffering capacity and avoid nutrient mining (Manna *et al*., 2007; Meena and Suthar, 2022; Ranjan *et al*., 2023) [26, 28, 30]. Residue management is a central element of INM as it improves soil moisture conservation and lack of burning of residues. it enriches soil moisture and prevents residue burning (Bhattacharyya *et al*., 2015) [8]. However, INM is restrained from the unavailability of organic sources, cost needed in its implementation and unfamiliarness among farmers. Inclusive of Long-Term Sustainability Excellent quality climate-resilient wheat production systems in intensive rice–wheat system by INM (Singh *et al.*, 2024; Bhardwaj *et al.*, 2023) [6, 25]

Also, INM promotes the resilience of wheat systems to drought and heat stress conditions through better soil water retention, carbon stabilization and soil biological activity which together contribute to climate-resilient wheat production systems.

Environmental Benefits of INM

INM mitigates the environmental degradation as a consequence of improved nutrient utilization through increased biological stabilization and conservation of nutrients through runoff, leaching, and volatilization. The higher content of organic matter in soil has a protective function against leaching losses of nitrogen compounds when we intensively produce wheat. INM also helps mitigate greenhouse gases by ensuring the synchronized supply and minimizing excess fertilizer application. Thus, inclusion of crop residues to INM results in less residue burning and pollution of air in rice-wheat production systems (FAO, 2022) [20].

Constraints and Limitations of INM Adoption

There are various advantages for practicing INM but some of the practical and socio-economic obstacles restrain its large-scale adoption. Challenges of this nature include insufficient supply of FYM, compost, crop residues and other sources of organic nutrients. The bulk transport and application of this kind of organic nutrient is high in labor cost. In addition to this, variations in nutrient content in organic manures and variability in field application of bio-fertilizers also hinder the efficient practice of INM. In addition, limited knowledge of farmers, lack of technical competency, poor extension services and scarcity of residues handling equipment also prevent the contact completion of INM practices in wheat-based systems. Lastly, the improper handling and slow degradation of residues are short term supply deficiencies with intensive cereal cropping. So adequate technology regarding Residue management is an important component on INM as it conserves soil moisture & minimizes residue burning.

Research Gaps and Future Priorities

While INM has been shown to provide substantial benefits for wheat productivity and soil health, some key research gaps still linger the majority of the existing literature on INM addresses its yield responses but fails to generate adequate information regarding its effects on sustainable microbial functional diversity, carbon stabilization, nutrient cycling, and greenhouse gas emissions across diverse individual IMP practices. Additionally, limited information is available on site-specific and climate-smart INM recommendations for wheat cropping systems diversification.

Future research should focus on integrating INM with other climate-smart agricultural innovations such as conservation agriculture, precision nutrient management, remote sensing technologies, where justified and possible within a sustainable wheat production system. In addition, research efforts should focus on micronutrient fertilizers, artificial intelligence-based nutrient recommendations and other decision-support tools. More long-term experiments are required to assess the carbon sequestration efficiency, environmental footprint and resilience of wheat cropping system under drought and heat stresses (Meena *et al*., 2023; Ranjan *et al.*, 2023) [27, 30].

Conclusion

Integrated nutrient management (INM) is an emerging practice that plays a crucial role in sustaining wheat productivity, enhancing soil fertility, and improving nutrient use efficiency. The combined use of mineral fertilizers, organic sources, crop residues, and biofertilizers improves the physical, chemical, and biological quality of soil while reducing nutrient losses and minimizing environmental degradation. Long-term studies on rice–wheat cropping systems have shown that INM enhances soil organic carbon levels and stabilizes crop productivity, thereby supporting the development of climate-resilient agriculture. Therefore, the adoption of INM practices is essential for achieving sustainable wheat production and maintaining long-term soil health under changing climatic conditions.

Table 7: Summary of Major INM Effects in Wheat-Based Systems

Focus area	Major contribution of INM	Key outcomes	Supporting references
Wheat productivity	Higher and stable yield	Improved tillering, grain filling and harvest index	Manna *et al*. (2007); Bajpai *et al.* (2006) [4, 26]
Soil organic carbon	Increased SOC and carbon pools	Improved soil fertility and resilience	Lal (2004); Ranjan *et al*. (2023) [24, 30]
Soil physical properties	Improved aggregation and porosity	Better water retention and root growth	Bhattacharyya *et al*. (2015); Sarkar *et al.* (2003) [8, 32]
Soil chemical fertility	Higher availability of N, P, K and	Improved nutrient balance and	Roy *et al*. (2006); Alloway (2008)

	micronutrients	nutrient cycling	[2, 31]
Soil biological health	Increased microbial biomass and enzyme activity	Enhanced nutrient mineralization and biological functioning	Goyal *et al*. (1992); Francioli *et al*. (2016) [14, 16]
Nutrient use efficiency	Improved nutrient recovery efficiency	Reduced nutrient losses and better fertilizer use	Singh *et al*. (2023); Meena *et al*. (2023) [27, 35]
Environmental sustainability	Reduced pollution and residue burning	Improved carbon sequestration and climate resilience	Lal (2004); Ranjan *et al*. (2023) [24, 30]

References

1. AICRP-LTFE. All India Coordinated Research Project on Long-Term Fertilizer Experiments to Study Changes in Soil Quality, Crop Productivity and Sustainability. ICAR-Indian Institute of Soil Science, Bhopal, India, 2022.
2. Alloway BJ. Zinc in soils and crop nutrition. 2nd ed. Brussels: International Zinc Association and Paris: International Fertilizer Industry Association, 2008.
3. Arancon NQ, Edwards CA, Bierman P, Welch C, Metzger JD. Influences of vermicomposts on field strawberries: Effects on growth and yields. Bioresource Technology,2004:93(2):145–153. https://doi.org/10.1016/j.biortech.2003.10.014
4. Bajpai RK, Chitale S, Upadhyay SK, Urkurkar JS. Long-term studies on soil physico-chemical properties and productivity of rice–wheat system as influenced by integrated nutrient management in Inceptisol of Chhattisgarh. Journal of the Indian Society of Soil Science,2006:54(1):24–29.
5. Bashan Y, Holguin G, de-Bashan LE. *Azospirillum*-plant relationships: physiological, molecular, agricultural and environmental advances (1997–2003). Canadian Journal of Microbiology,2004:50(8):521–577. https://doi.org/10.1139/w04-035
6. Bhardwaj AK, Malik K, Chejara S *et al*. Integration of organics in nutrient management for rice-wheat system improves nitrogen use efficiency via favorable soil biological and electrochemical responses. Frontiers in Plant Science,2023:13:1075011. https://doi.org/10.3389/fpls.2022.1075011
7. Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N. Biofertilizers function as key players in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microbial Cell Factories,2014:13(1):1–10. http://www.microbialcellfactories.com/content/13/1/66
8. Bhattacharyya R, Das TK, Sudhishri S, Dudwal B, Sharma AR, Bhatia A *et al*. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. European Journal of Agronomy,2015:70:11–21. https://doi.org/10.1016/j.eja.2015.06.006
9. Bhattacharyya R, Tuti MD, Bisht JK, Bhatt JC, Gupta HS. Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. Soil Science Society of America Journal,2012:76(2):617–627. https://doi.org/10.2136/sssaj2011.0320
10. Cassman KG, Dobermann A, Walters DT. Agroecosystems, nitrogen-use efficiency and nitrogen management. AMBIO: A Journal of the Human Environment,2002:31(2):132–140. https://doi.org/10.1579/0044-7447-31.2.132
11. Dhaliwal SS, Sharma S, Sharma V, Shukla AK, Walia SS, Toor AS *et al*. Long-term integrated nutrient management in the maize–wheat cropping system in alluvial soils of north-western India: Influence on soil organic carbon, microbial activity and nutrient status. Agronomy,2021:11(11):2258. https://doi.org/10.3390/agronomy11112258
12. Edwards CA, Arancon NQ, Sherman RL. Vermiculture technology: earthworms, organic wastes and environmental management. Boca Raton: CRC Press, 2011.
13. FAO. Sustainable soil fertility management for climate-resilient agriculture. Rome: Food and Agriculture Organization, 2022.
14. Francioli D, Schulz E, Lentendu G, Wubet T, Buscot F, Reitz T. Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies. Frontiers in Microbiology, 2016, 7, 1446. https://doi.org/10.3389/fmicb.2016.01446
15. Ghosh T, Das D, Aggarwal P, Sarkar A, Jha PK, Prasad PVV. Evaluation of soil quality frameworks in rice–wheat systems under integrated nutrient management in Indo-Gangetic Plains. Scientific Reports,2025:15:21630. https://doi.org/10.1038/s41598-025-21630-1
16. Goyal S, Mishra MM, Hooda IS, Singh R. Organic matter–microbial biomass relationships in field experiments under tropical conditions: effects of inorganic fertilization and organic amendments. Soil Biology and Biochemistry,1992:24(11):1081–1084. https://doi.org/10.1016/0038-0717(92)90056-4
17. ICAR. Soil health management for sustainable cereal production systems. New Delhi: Indian Council of Agricultural Research, 2023.
18. ICAR-IISS. Annual Report 2021. ICAR-Indian Institute of Soil Science, Bhopal, India, 2021.
19. Jat HS, Kumar V, Datta A, Choudhary M, Yadvinder-Singh, Kakraliya SK *et al*. Designing profitable, resource use efficient and environmentally sound cereal based systems for the Western Indo-Gangetic Plains. Scientific Reports,2020:10:19267. https://doi.org/10.1038/s41598-020-76035-z
20. Jat L, Naresh RK, Bhatt R, Chandra MS, Singh S, Gupta SK *et al*. Wheat nutrient management strategies to increase productivity, profitability and quality on sandy loam soils. Agronomy,2022:12(11):2807. https://doi.org/10.3390/agronomy12112807
21. Jat ML, Singh VK, Sharma PC, Parihar CM. Conservation agriculture and integrated nutrient management for improving wheat productivity and soil health. Sustainability,2022:14(9):5124–5138. https://doi.org/10.3390/su14095124
22. Kaur P, Saini KS, Sharma S, Kaur J, Bhatt R, Alamri S *et al*. Increasing the efficiency of the rice–wheat

cropping system through integrated nutrient management. Sustainability,2023:15(17):12694. https://doi.org/10.3390/su151712694

23. Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B *et al*. How extensive are yield declines in long-term rice–wheat experiments in Asia? Field Crops Research,2003:81(2–3):159–180. https://doi.org/10.1016/S0378-4290(02)00219-8
24. Lal R. Soil carbon sequestration to mitigate climate change. Geoderma,2004:123(1–2):1–22. https://doi.org/10.1016/j.geoderma.2004.01.032
25. Lodhi S, Singh R, Yadav A, Maurya DK, Pal RK, Kumar S. Effect of integrated nutrient management on growth, yield attributes and soil quality of wheat (*Triticum aestivum* L.). International Journal of Research in Agronomy,2024:7(6):436–442. https://doi.org/10.33545/2618060X.2024.v7.i6f.906
26. Manna MC, Swarup A, Wanjari RH, Mishra B, Shahi DK. Long-term fertilization, manure and liming effects on soil organic matter and crop yields. Soil and Tillage Research,2007:94(2):397–409. https://doi.org/10.1016/j.still.2006.08.013
27. Meena RB, Pandey RN, Trivedi A, Chobhe KA, Sharma VK, Parihar CM. Integrated nutrient management prescription for late-sown wheat (*Triticum aestivum*). Indian Journal of Agricultural Sciences,2023:93(5):506–511. https://doi.org/10.56093/ijas.v93i5.132398
28. Meena SK, Suthar S. Effect of nutrient management on soil carbon quantities, qualities and stock under rice–wheat production system. Agriculture,2022:12(11):1822. https://doi.org/10.3390/agriculture12111822
29. Naresh RK, Gupta RK, Singh SP, Kumar V, Kumar A, Mahajan NC. Conservation agriculture and crop residue management for sustainability of rice–wheat cropping systems in the Indo-Gangetic Plains of India. International Journal of Current Microbiology and Applied Sciences,2017:6(12):446–460. https://doi.org/10.20546/ijcmas.2017.612.054
30. Ranjan SK, Kumar S, Dutta SK, Padhan SR, Dayal P, Sow S *et al*. Influence of 36 years of integrated nutrient management on soil carbon pools, environmental footprint and agronomic productivity of wheat under rice–wheat cropping system. Frontiers in Environmental Science,2023:11:1222909. https://doi.org/10.3389/fenvs.2023.1222909
31. Roy RN, Finck A, Blair GJ, Tandon HLS. Plant nutrition for food security: A guide for integrated nutrient management. Rome: Food and Agriculture Organization (FAO), 2006.
32. Sarkar S, Singh SR, Singh RP. The effect of organic and inorganic fertilizer on soil physical condition and productivity of a rice–lentil cropping sequence in India. Journal of Agricultural Science,2003:140:419–425. https://doi.org/10.1017/S0021859603003186
33. Sarkar S, Skalicky M, Hossain A, Brestic M, Saha S, Garai S *et al*. Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability,2020:12(23):9808. https://doi.org/10.3390/su12239808
34. Singh B. Are nitrogen fertilizers deleterious to soil health? Agronomy,2018:8(4):48. https://doi.org/10.3390/agronomy8040048
35. Singh G, Shrivastava M, Langyan S, Sharma A, Pandey R, Darjee S. Integrated nutrient management reduced nutrient losses and increased crop yield in irrigated wheat. Archives of Agronomy and Soil Science,2023:69(8):1298–1309. https://doi.org/10.1080/03650340.2022.2084535
36. Tandon HLS. Soil nutrient balance sheets in India: Importance, status, issues and concerns. Better Crops India,2007:1:15–19.