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Integrated Nutrient Management in Wheat Farming

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Abstract Wheat (*Triticum aestivum* L) is a very important food crop in the world. Whether wheat can achieve high and stable yields largely depends on the management of nutrients in the soil. Integrated Nutrient Management (INM) can increase wheat yield and better protect the soil environment. A reasonable combination of organic fertilizer, chemical fertilizer and bio-fertilizer can significantly increase the grain yield and protein content of wheat. Compared with the single application of chemical fertilizers, INM is more effective in reducing the amount of chemical fertilizers used and can also lower the risk of nutrient loss. The research explored various precise nutrient management measures. It is necessary to promote the integration of INM and climate-smart agriculture to meet the wheat production demands of different regions and provide a reference for optimizing the nutrient management model of wheat.
Keywords Wheat (*Triticum aestivum* L); Integrated Nutrient Management; Nutrient Use Efficiency; Soil Health; Sustainable Agriculture

1 Introduction

Approximately 40% of the population takes wheat as their main staple food. Wheat grains can provide an energy source for humans and livestock, and are also an important source of protein and mineral elements (Hassouni et al., 2025). The gluten protein contained in wheat has good extensibility and viscosity, which makes it very suitable for processing into noodles and a variety of foods.

In agricultural production, if only chemical fertilizers are used for a long time, it is easy to bring about a series of problems. The organic matter in the soil will continuously decrease, some macronutrients and micronutrients will gradually be deficient, the soil structure will also be damaged, and the biological activity in the soil will significantly decline (Sharma et al., 2020; Kumar et al., 2022). In irrigated wheat cultivation and long-term crop rotation systems, the fertilization methods are often dominated by nitrogen, phosphorus and potassium, but the input of organic fertilizers and the supplementation of medium and trace elements are also easily overlooked. Integrated Nutrient Management (INM) uses chemical fertilizer together with manure, compost, crop residues, green manure, and helpful soil microbes. In wheat systems, including wheat grown with rice, maize, or peanuts, INM can raise grain yield and nutrient uptake (Sharma et al., 2019).

This study reviews the main scientific and practical challenges of nutrient management for wheat as a global staple food, comprehensively analyzes the impacts of INM on wheat yield, quality, nutrient use efficiency, soil health, and economic benefits, as well as its environmental effects, and proposes future research and technology integration directions oriented towards regional differences and climate change scenarios. This provides a theoretical basis and practical reference for developing sustainable wheat nutrient management strategies adapted to different ecological zones and production types.

2 Nutrient Requirements and Absorption Characteristics of Wheat

2.1 Major macroelements (N, P, K) and their physiological functions

In wheat production, the rational combination and application of nitrogen, phosphorus and potassium nutrients can enhance dry matter accumulation and nutrient absorption. In the treatment of applying 125 kg $N{\cdot}ha^{-1}$ in combination with 50 kg $K_2O{\cdot}ha^{-1}$, the wheat yield could reach 6.3 t/ha. At this time, the contents of nitrogen, phosphorus and potassium in the grains were approximately 15.5, 3.6 and 5.8 g/kg respectively (Rawal et al., 2022). Nitrogen and phosphorus are mainly concentrated in the grains, while the content of potassium in straw is usually higher than that in the grains. There is a clear physiological interaction between the form of nitrogen and the supply of potassium. When the potassium supply level is relatively high, it can reduce the toxic effect of $NH4^+$ on plants and simultaneously improve the utilization efficiency of NO_3^- (Cao et al., 2025).

2.2 Minor and micronutrients (S, Zn, Fe, Mn, Cu, B)

Sulfur is a component of sulfur-containing amino acids and various coenzymes, and is closely related to protein content and baking quality. Under an optimal nitrogen and water content of 120 kg N + 30 kg S·ha^{-1}, N and S absorption, as well as NUE and SUE, reach their highest levels throughout the plant's growth period (Sai et al., 2025). Zinc participates in membrane stability, hormone metabolism, and phytochrome activity; iron and manganese are key components of the photosynthetic electron transport chain and various redox enzymes, while copper plays a role in photosynthesis and respiration, lignin synthesis, and pollen viability. Boron has specific functions in cell wall formation, pollen tube elongation, and grain development; deficiency leads to inhibited heading and grain setting. S, Zn, and B are generally deficient in many regions, and multiple micronutrient deficiencies are common, representing latent factors limiting wheat yield and nutritional quality (Shukla et al., 2021). Approximately 3 billion people worldwide are affected by Zn and Fe deficiencies, and wheat grains naturally have low levels of Zn and Fe. In some major producing areas, the average Zn and Fe content measured is significantly lower than the recommended values for human health (Wysocka et al., 2025). In low-fertility or calcareous soils, soil or foliar application of Zn, Fe, Mn, Cu, and B can improve plant absorption and grain enrichment. Foliar spraying of a micronutrient mixture can increase the Zn, Cu, Fe, Mn, and B content in grains by 21%~47% (Raza et al., 2025).

2.3 Nutrient requirement rhythms during wheat growth stages

Wheat seedlings to tillering stages are particularly sensitive to phosphorus and some nitrogen. Sufficient P and adequate N promote root development, tillering, and canopy formation. After entering the jointing-heading stage, the accumulation of dry matter and the absorption rate of N and K in the aboveground parts accelerate significantly, forming the absorption peak of the entire growth period (Kumar et al., 2023). From heading to flowering to grain filling, the net absorption of exogenous nutrients by the plant gradually weakens, and the N, S, Zn, Fe, Mn, and Cu in the grains mainly rely on the retransportation of nutrients stored in vegetative organs (leaves, stems, and glumes). The absorption peaks of macronutrients and micronutrients also show stage differences. During the grain filling stage, wheat absorbs Zn and Mn most vigorously, while Cu absorption is more sensitive around the jointing stage.

3 Key Components of Integrated Nutrient Management in Wheat

3.1 Chemical fertilizers

Under alkaline soil and saline-alkali land conditions, appropriately increasing the application of nitrogen and phosphorus fertilizers can significantly promote the growth of wheat. The application of 180 kg N·ha^{-1} in combination with 80 kg P·ha^{-1} has a better effect in terms of yield increase and nutrient absorption (Hou et al., 2025). In calcareous soil, nitrogen sources mainly composed of nitrate nitrogen are more conducive to nutrient absorption by crops than ammonium nitrogen. The use of nitrate nitrogen can improve the utilization rate of N, P and K by wheat (Alvi et al., 2025).

In dryland areas, soil fertility is often limited. This problem is more serious in fields with long-term continuous cropping. In these fields, applying NPK fertilizer at the recommended rate is necessary. At the same time, adding organic fertilizer brings clear benefits. This practice helps crops grow better and also improves the soil. Soil organic carbon increases. Available nitrogen, phosphorus, and potassium also rise. Some trace elements, such as zinc and iron, become more available as well (Walia et al., 2024). Among different treatments, replacing 50% of chemical NPK with farmyard manure gives the best result. Nitrogen management is also important for winter wheat. Applying all nitrogen at one time is not a good choice. Splitting nitrogen into several applications works better in most cases. Base fertilizer is applied first. Top dressing is then added later. This approach helps wheat get enough nitrogen at key stages, especially during jointing and booting (Fasani et al., 2025). In rotation systems such as wheat–corn or wheat–rice, fertilizer use can be planned across seasons. Nitrogen, phosphorus, and potassium do not need to be fully applied in one season. Part of the fertilizer can be moved to periods with lower crop demand. The corn season is one such period (Zhang et al., 2025). In addition, fertilizer placement matters. Compared with surface broadcasting, furrow application, trench placement, and deep application usually give better results.

3.2 Organic nutrient sources

In rice-wheat and corn-wheat rotations, farmyard manure, green manure or wheat straw can be used to replace 25% to 50% of the recommended NPK dosage (Bhardwaj et al., 2023). Farmyard manure has the most obvious effect on increasing soil organic carbon (SOC) and microbial carbon and nitrogen. The effect of returning wheat straw to the field is slightly weaker. Green manure can also significantly improve the overall soil quality (Dhaliwal et al., 2021). In the corn-wheat system, when 50% NPK is used in combination with poultry manure, oil cakes, or wheat and corn stalks, both soil organic carbon and microbial biomass carbon are significantly increased. Compared with the application of NPK alone, the average wheat yield increased by approximately 23%. Long-term continuous application of farmyard manure can increase the SOC content from 0.44% to 0.66%, and the contents of mineralized nitrogen and available phosphorus and potassium also increase accordingly (Dhaliwal et al., 2021).

3.3 Biofertilizers and microbial inputs

When Azotobacter or Azospirillum is used with chemical fertilizers, the effect is usually steady. The results do not change much between seasons. In most cases, chemical fertilizer can be kept at 75%~100% of the recommended rate. Under this level, nitrogen fertilizer can be cut by about 15%~25%. Yield does not go down. In some trials, it even goes up (Saini et al., 2025). In corn–wheat rotation systems and in orchards, phosphorus fertilizer is often not used alone. It is applied together with phosphorus-solubilizing bacteria. Trichoderma and similar microbes are also added. This helps phosphorus work better in the soil. Because of this, less phosphorus fertilizer is needed. Crops take up more phosphorus. Seed yield also shows an increase (Imran, 2024). In wheat production, the same pattern is often seen. Azotobacter and PSB are combined with about 75% of the recommended NPK rate. This already gives good results. When farmyard manure or vermicompost is added, the effect becomes stronger. Many field experiments report this result. When chemical fertilizer is kept at 75%~100% of the recommended level and is used together with organic fertilizer and bio-fertilizers such as Azotobacter, PSB, and AMF, wheat yield is usually the highest. Nutrient uptake by the crop is also better under these conditions (Varinderpal-Singh et al., 2020).

4 Integrated Nutrient Management Strategies in Wheat Cropping Systems

4.1 Combined application of organic-inorganic-bionutrient sources

In trials conducted in multiple locations in India, wheat treatments using 75% of the recommended fertilizer dose (RDF) combined with 5 t/ha of vermicompost and inoculated with nitrogen-fixing and phosphorus-solubilizing bacteria (Azospirillum/Azotobacter + PSB) showed higher grain yield and net income than those using 100% RDF alone, and were comparable to or slightly better than the treatment using 75% RDF + 10 t/ha of farmyard manure (FYM) + biofertilizer. The 85% RDF + 15% organic nitrogen source (vermicompost) treatment (N3) significantly improved wheat growth, yield, and economic returns (Saini et al., 2025). The cumulative available nitrogen during the season was approximately 962 μg cm^{-2} for the green manure (GM) treatment, higher than the 878 μg cm^{-2} for the 100% full fertilizer treatment. The total seasonal nitrogen supply (872 and 865 μg cm^{-2}) for the legume residue (LE) and FYM treatments was also close to or slightly lower than that of the full fertilizer treatment (Bhardwaj et al., 2021). Under irrigated wheat conditions, the combined application of the recommended amount of NPK with Azotobacter and arbuscular mycorrhizal fungi reduced ammonia volatilization loss to 10.2~10.6 kg N ha^{-1} and denitrification loss to only 2.4~2.5 kg N ha^{-1}, significantly lower than the NPK monotherapy treatment, while increasing grain yield to 6.4 t ha^{-1} (Darjee et al., 2022). Meta-analysis covering 338 experimental data pairs from 1989–2016 showed that, compared to the "no organic fertilizer only," "organic fertilizer only," and no fertilization treatments, INM increased wheat yield by 2.5%, 29.2%, and 90.9% in loam soils, and by 0.6%, 24.9%, and 93.7% in clay soils, respectively, with a net gain of 127% compared to no fertilization (Sharma et al., 2019) (Figure 1).

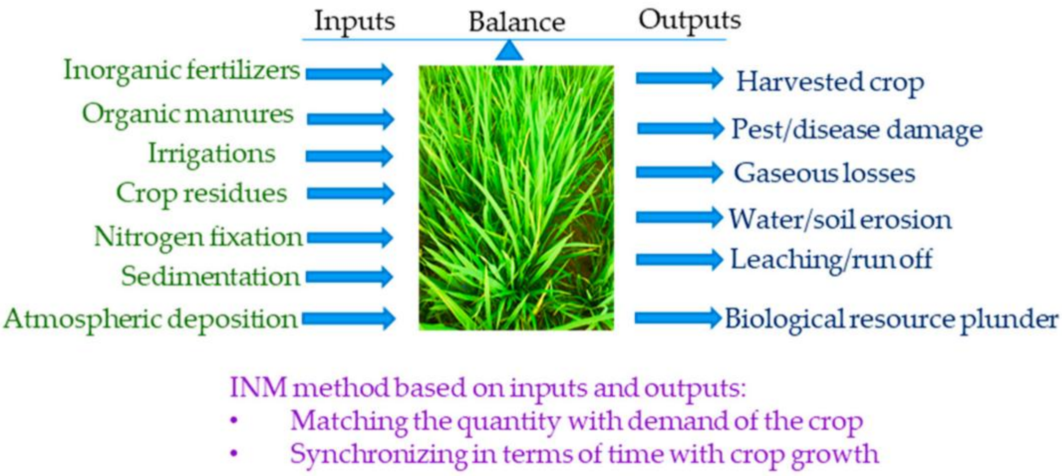

Figure 1 Mean of nutrients for inputs and outputs, and the principles of integrated nutrient management systems (Adopted from Sharma et al., 2019)

4.2 Nutrient management based on soil testing and field differences

In a 36-year INM trial of rice-wheat in eastern India, compared to the treatment with 100% RDF in both rice and wheat seasons, the treatment with 50% RDF + 50% nitrogen replaced by FYM throughout the entire season resulted in a 46.4% increase in wheat soil organic carbon content (an increase of 18.29 Mg ha^{-1}), an annual average carbon sequestration rate of 0.22 Mg ha^{-1} yr^{-1}, and significant improvements in the agronomic efficiency of nitrogen, phosphorus, and potassium, as well as the productivity of some factors. When 50% RDF + 50% FYM replaced 100% RDF alone during the wheat season, wheat grain yield increased by 24.7%, while greenhouse gas emission intensity decreased significantly (Ranjan et al., 2023). In a dryland maize-wheat system in North India, 17 years of INM treatment (fertilizer combined with FYM) increased organic carbon in the 0~15 cm soil layer from 0.44% to 0.66%, while available N, P, and K increased to 164.9, 31.4, and 168.0 kg/ha, respectively. DTPA-based treatment also significantly increased available Zn, Cu, Fe, and Mn, while decreasing soil pH, EC, and bulk density, and increasing water holding capacity and total porosity (Dhaliwal et al., 2021). In a sensor-variable nitrogen application study involving 57 fields, canopy sensor-based N management reduced nitrogen use efficiency by an average of 40 kg N ha^{-1} in maize without yield reduction, significantly improving nitrogen use efficiency. However, the increase in efficiency in wheat was not statistically significant and was strongly controlled by field yield level, yield spatial variability, and soil texture (Paccioretti et al., 2025).

4.3 Conservation agriculture and crop residue management

Under wide-ridge no-till farming, wheat shows better root growth when the soil surface is fully covered by crop residues. When the full recommended nitrogen rate is applied together with residue retention (PBB + R + 100N), wheat root length density increases a lot. It is about 60% higher than that under traditional tillage. At the same time, the total yield of the three-crop system also goes up clearly. The increase reaches about 31.1%. When nitrogen input is reduced to 75% of the recommended level, but crop residues are still kept on the field, crops use nutrients more efficiently. In this case, the use efficiency of nitrogen, phosphorus, and potassium is even higher than with full nitrogen input (Ghosh et al., 2025). In long-term rice–wheat nutrient management systems, part of the straw is returned to the soil. About one-third of wheat straw or one-third of rice straw is added back during the rice season. Nitrogen fertilizer is then applied at levels ranging from 55% to 100% of the recommended rate. As a result, nitrogen supply during the wheat season increases clearly. It reaches 649 μg cm^{-2} with wheat straw and 687 μg cm^{-2} with rice straw. Under these conditions, wheat nitrogen use efficiency improves strongly, increasing by about 1.3 to 2.0 times (Bhardwaj et al., 2021).

4.4 Integration with crop rotation and intercropping systems

In a 40-year long-term rice-wheat trial, treatments using 50% RDF + 50% FYM (or combined with wheat straw and green manure Sesbania) during the rice season and 100% RDF during the wheat season resulted in a wheat grain yield of 4435 kg/ha (Manohar et al., 2025). In the maize-wheat system, a nitrogen management strategy combining 50% organic nitrogen (compost) and 50% inorganic nitrogen with bio-fertilizer resulted in grain yields of 7168 and 6405 kg/ha for maize and wheat, respectively, and soil organic carbon increases of 2.75% and 1.59%, respectively. Net benefits of \$779 and \$961 ha^{-1} were also achieved, exceeding those of chemical fertilizer application alone (Sarwar et al., 2021). Multi-year maize-wheat trials replacing 25%~50% NPK with biochar showed that a 75% NPK + 5 t/ha biochar treatment increased dry matter by 57%, thousand-grain weight by 54%, and grain yield by 63% in wheat (Sarwar et al., 2023). In the rice-wheat system, the application of poultry manure plus different levels of nitrogen during the rice season not only increased rice yield by 61%~67% compared to the no-organic treatment, but also improved apparent nitrogen recovery and yield equivalent through higher N, P, and K uptake (N 177.4 kg/ha, P 31.6 kg/ha, K 179.6 kg/ha), resulting in a residual yield increase of 24.3%~24.4% in the subsequent wheat season (Kaur et al., 2023). Direct data on intercropping INM with wheat are still relatively limited, but in the peanut-wheat sequence, systematic INM (75% RDF + 5 t/ha FYM + PGPR in peanut, 100% RDF in wheat) increased system productivity by 17.1% and system profitability by 22.6% compared to farmers' usual practices, and improved nutrient uptake and soil fertility in subsequent wheat crops (Jat et al., 2023).

5 Impact of Integrated Nutrient Management on Wheat Productivity

5.1 Grain yield response and yield composition

From 2022 to 2024, field trials on INM were done in northern India. Several fertilizer plans were tested. The results were clear. Using different fertilizers together worked better than using only one type. The best treatment included chemical fertilizer, organic fertilizer, and bio-fertilizer. This combination gave good results in both growing seasons. In contrast, the control group showed poor performance. Grain protein content in the control was only 7.6%~7.8%. Protein yield was also low, at about 208~224 kg/ha (Sharma and Tomar, 2025). A two-year experiment was carried out in Haryana. The treatment effect was easier to see in this region. Better results were obtained when the full recommended nitrogen dose was applied. In addition, 25% of nitrogen was supplied through vermicompost. Compared with plots without fertilizer, this treatment showed strong improvements. The number of effective panicles nearly doubled, with an increase of 94.96%. Panicle length increased by 34.14%. The 1 000-grain weight went up by 25.47%. Grain yield increased by 165.21%, and straw yield increased by 157.13% (Fazily, 2021). In the pearl millet–wheat rotation system, another fertilizer pattern was tested. During the wheat season, 75% RDF was applied together with 5 t FYM ha^{-1}. Bio-fertilizers, including Azotobacter and PSB, were also added. Under this treatment, grain yield reached 4.12 t/ha. This yield was similar to that obtained with the 100% RDF + FYM + bio-fertilizer treatment. However, it was clearly higher than the yield from using 100% RDF alone (Saharan et al., 2023).

5.2 Nutrient use efficiency and fertilizer recovery rate

The INM treatment using 120-90-60 kg/ha NPK + 5 kg Zn + 1 kg B + bio-fertilizer + FYM resulted in a grain yield of 4.9 t/ha, representing an increase of approximately 25% compared to farmers' conventional fertilization practices and 9%~11% compared to recommended chemical fertilizer systems. Nitrogen use efficiency was significantly improved, with apparent recovery rate and nutrient uptake (N, P, K content) reaching the highest levels (Ahmed et al., 2023). On typical Vertisol, the treatment of 75% NPK + 5 t FYM ha^{-1} + PSB + Azotobacter + Zn resulted in wheat uptake of N, P, K, S, and Zn reaching 147.1, 28.4, 174.6, 51.9 kg/ha, and 335.6 g/ha, respectively, significantly higher than that of 100% NPK alone (Sharma et al., 2013). Jat et al. (2022) achieved an agronomic efficiency of 3.2 kg, an apparent physiological efficiency of 14.0 kg, and an apparent recovery rate of 0.23 in wheat grown in loamy sandy soil using an INM combination of 5 t/ha FYM + NPK compound fertilizer + NPK bio-fertilizer + multiple foliar applications of urea and NPK, which was significantly improved compared to single application of chemical fertilizers. In a meta-analysis of multi-location data prior to 2024, the practice of "integrated nitrogen management," which combines optimized nitrogen application with irrigation, straw return to the field, and organic fertilizer, increased wheat yield by an average of 5.4% and improved NUE by 55%. Furthermore, under conditions of SOC ≥10 g/kg, annual precipitation ≤400 mm, and average annual temperature 10 ℃~15 ℃, yield increases reached 8.5%, 6.4%, and 5.8%, respectively, without a decrease in water use efficiency (Liu et al., 2024).

5.3 Effects on grain quality (enrichment of protein and micronutrients)

In the Vertisol soil, when 5 t/ha of vermicomworm manure was used, along with green manure, combined with 50% NP fertilizer, and simultaneously treated with INM of Jivamrut and Azophos, the protein content of wheat grains was the highest, reaching 11.81%. The absorption amounts of nitrogen, phosphorus and potassium by wheat were 78.84, 20.52 and 77.82 kg/ha respectively, while under the lowest treatment, the absorption amounts of nitrogen, phosphorus and potassium were only 48.40, 10.38 and 48.80 kg/ha respectively, and the gap was relatively obvious. In terms of the amino acid composition of grains, the contents of methionine, cysteine and lysine varied between 1.36~1.45, 1.41~1.47 and 2.42~2.53 g/16 g N respectively (Gund et al., 2022). When 50% NPK was applied in combination with farmyard manure, or wheat straw and green manure were added simultaneously, the content of soil organic carbon increased, and the contents of available nitrogen, phosphorus, potassium and DTPA-Zn also increased accordingly (Walia et al., 2024).

5.4 Yield stability under different climatic and ecological conditions

The INM experiment in the semi-arid area set up 5, 10, 15 and 20 t/ha farmyard manure (FYM) and used it in combination with different levels of NPK fertilizers. The experiment adopted a three-time irrigation method, which was carried out respectively at the seedling emergence stage, the tillering stage and the jointing stage. Under the condition of three irrigates, when 10 t/ha FYM was applied in combination with 80-60-40 kg of N-P_2O_5-K_2O of ha^{-1}, the grain yield of wheat was the highest, and the absorption of nitrogen, phosphorus and potassium by crops also reached the maximum. This treatment is relatively stable in different rainfall years and has a small impact on interannual rainfall variations (Ali et al., 2024). The wheat experiment on industrial wastewater irrigation compared different combinations of irrigation water and fertilization methods. When wastewater accounted for 25% and clear water 75% (IW1) in the irrigation water, and the fertilization method was 75% recommended chemical fertilizer plus 25% vermicomposted manure (INM2), the growth condition of wheat was the best. In two consecutive years, plant height, tillering number, leaf area index and grain yield all reached the highest levels (Kurmi et al., 2025).

6 Impact of INM on Soil Health and Sustainability

6.1 Soil fertility restoration and maintenance

In the semi-arid pearl millet-wheat system, the application of different organic sources and NPs over 25 years resulted in a gradient increase in topsoil TOC within the range of 0.46–1.42%, with corresponding available N, P, K, and S reaching 194.7, 74.9, 761.2, and 54.6 kg/ha, respectively; the correlation coefficients between TOC and available N, P, K, and S were all greater than 0.77 (R^2 against N, P, K, and S were 0.769, 0.881, 0.758, and 0.914, respectively) (Kumari et al., 2024). In a 34-year rice-wheat trial in the Indo-Ganges Plain, the treatment of 50% recommended NPK + 50% FYM showed the best water-soluble aggregates and exchangeable, non-exchangeable, fixed, and total K states in both rice and wheat. Furthermore, the Fe and Zn activity pools increased to 984.8 mg/kg and 3.08 mg/kg, respectively, in the CFeOX fractionation, which were significantly higher than the full fertilizer treatment (Walia et al., 2024). A 31-year rice-wheat experiment further showed that the average annual C sequestration rate of the 50% NPK + 50% FYM treatment in the rice season and the 100% NPK treatment in the wheat season was 0.29 MgC ha^{-1} yr^{-1}, higher than the 0.13 MgC ha^{-1} yr^{-1} of 100% NPK. Furthermore, organic carbon was positively correlated with permeability and water-stable aggregates, and negatively correlated with bulk density and soil strength (Sandhu et al., 2020).

6.2 Changes in soil organic carbon and nutrient availability

In the continuous six-year experiment of pearl millet and wheat, when both farmyard manure (FYM) and chemical fertilizer (NPK) were applied simultaneously, there were significant increases in TOC, Walkley-black organic carbon, easily decomposable organic carbon (LBC), and microbial biomass carbon (MBC). Under the treatment of FYM+NPK, the LBC was 1.36 g/kg and the MBC was 273 mg/kg, both of which were higher than those treated with only FYM or only NPK. The positive correlation between LBC and MBC and wheat yield was the most obvious (Moharana et al., 2012). Under the integrated nutrient management of rice-wheat for 10 years, the green manure turning treatment provided the highest available nitrogen throughout the growth period, cumulatively reaching 962 μg cm^{-2}, even higher than the 878 μg cm^{-2} of 100% chemical fertilizer application. The biomass returns of leguminous crops to the field and the application of FYM were 872 and 865 μg cm^{-2}, respectively, which were basically close to the total chemical fertilizer treatment and slightly higher in some cases (Bhardwaj et al., 2021). Replacing 50% of chemical fertilizer nitrogen with FYM or green manure can significantly increase various activated carbon components, including POM-C, MBC, $KMnO_4$ oxidizable carbon and DOC. The carbon management index of each treatment was generally above 130, and the sustainable Yield Index (SYI) was also all greater than 0.5. In addition, SYI shows a strong correlation with $KMnO_4$-C, DOC, dehydrogenase activity (DHA), and POM-C, with r^2 of 0.69, 0.66, 0.65, and 0.64 respectively (Das et al., 2025).

6.3 Soil microbial diversity and enzyme activity

In the wheat season irrigation × nutrient management experiment, 50% of the recommended nitrogen was treated with an integrated nutrient source (INS) replaced by FYM. The microbial biomass C in the soil reached 73 μg/g, dehydrogenase 86 μg TPF g^{-1} d^{-1}, and acidic and alkaline phosphatases 39.6 and 81.8 μg PNP g^{-1} h^{-1}, respectively, all of which were significantly higher than those of applying chemical fertilizers alone. It is notable that the soil available nitrogen left by a single CRI irrigation combined with INS treatment was the highest (149.3 kg/ha) (Kumar et al., 2021). In a 13-year trial involving leguminous crop rotation × nutrient management, the combination of leguminous crop rotation (pigeon bean-wheat, corn-wheat-mung bean) +INM significantly increased SOC, SMBC and SMBN compared with a single corn - wheat rotation. The activities of alkaline phosphatase, aryl sulfatase, β -glucosidase, dehydrogenase and protease were increased by 9%~80% compared with monoculture corn-wheat, and the nutrient management sequence was generally INM> recommended fertilizer ≈ control (Borase et al., 2020).

7 Future Perspectives and Research Directions

7.1 Precision nutrient management and digital agriculture tools

A field test using the Nutrient Expert® (NE) system involved 1,594 farmers. In most cases, the results were positive. More than 80% of the plots produced more wheat than before. Farmers also earned more money from these fields. If this system is used more widely in India, especially in rice–wheat rotation areas, fertilizer use can be cut down. Nitrogen fertilizer could be reduced by about 1.44 Mt each year. At the same time, total grain output may increase by nearly 13.92 Mt. This also helps the environment. CO_2-equivalent emissions could drop by around 5.34 Mt every year (Sapkota et al., 2021). In Ethiopia, farmers growing wheat and millet together are using a simple mobile phone app. The app gives fertilizer advice based on how steep the land is. These suggestions are sent by text message. Farmers can easily follow them. After using the app, wheat yields went up clearly. Yields increased by 23% on lower slopes and by 21% on middle slopes. The cost–benefit ratio reached 10:1. This means farmers spent less but earned more overall (Desta et al., 2023). Besides this, new tools are also being used in wheat production. Remote sensing and unmanned aerial vehicles (UAVs) help farmers and technicians watch crop growth over time. They make it easier to understand nutrient conditions and respond faster when problems appear.

7.2 Integration of INM with climate-smart agriculture

The corn-wheat rotation in the Ganges Plain of India was compared with different farming and nutrient management methods. By using permanent high beds, while retaining the straw, and in combination with Nutrient Expert® and GreenSeeker™ for precise fertilization, the system yield increased by 23.2% compared with conventional ploughing without returning the straw. The potential for global warming has decreased by 32%, and the intensity of greenhouse gas emissions has dropped by 45%~47% (Hasanain et al., 2025). Under conditions of limited phosphorus supply and unstable climate change, by integrating phosphorus-dissolving bacteria (PSB), soil nutrient information and meteorological data, wheat yields have generally increased by 5%~15% in different ecological regions, such as irrigated plains, arid mountainous areas and delta regions, and the phosphorus content in grains has also increased. Future climate-intelligent integrated nutrient management (CSA-INM) requires greater emphasis on microbial regulation and integration with regional climate adaptation measures (Yahya et al., 2023).

7.3 Policies and promotion strategies for promoting INM expansion

In the rice-wheat rotation system, the use of INM is much more effective than no fertilization. The net income from wheat can be increased by 127%. Compared with using inorganic fertilizers alone, the revenue can also increase by approximately 9.3%. Meanwhile, INM can also improve soil conditions, including increasing soil organic carbon content, available nitrogen, phosphorus and potassium levels, and microbial biomass carbon content (Sharma et al., 2019). INM and SSNM should be officially incorporated into the national fertilizer recommendation system and combined with emission reduction targets. Goals such as reducing nitrogen fertilizer application, lowering N_2O emissions, and increasing soil organic carbon storage (Kaur et al., 2025). During the promotion process, practical training can be carried out by relying on platforms such as demonstration fields, farmers' field schools and cooperatives. It can be combined with credit and agricultural insurance measures to help farmers share the risks they may face in the early stage of transformation.

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