Available online at www.agrifarming.org

DOI: http://dx.doi.org/10.18782/2582-7146.275

ISSN: 2582 – 7146

Curr. Rese. Agri. Far. (2026) *7*(1), 47-55

Review Article

Current Research in Agriculture and Farming

Peer-Reviewed, Refereed, Open Access Journal

Integrated Nutrient Management for Enhanced Crop Productivity

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Received: 27.10.2025 | Revised: 23.12.2025 | Accepted: 6.01.2026

ABSTRACT

Integrated Nutrient Management (INM) is a sustainable approach that integrates organic manures, inorganic fertilizers, biofertilizers, and crop residues to optimize nutrient availability, improve soil health, and enhance crop productivity. Excessive reliance on chemical fertilizers has contributed to soil degradation, nutrient imbalance, environmental pollution, and stagnating crop yields. INM addresses these challenges by synchronizing nutrient supply with crop demand through the balanced use of diverse nutrient sources. This review highlights the major components of INM, including farmyard manure, vermicompost, green manures, biofertilizers such as Azotobacter *and phosphorus-solubilizing bacteria, and chemical fertilizers. Evidence indicates that INM significantly improves crop yield, nutrient use efficiency, soil organic carbon, microbial activity, water-holding capacity, and overall soil fertility while reducing greenhouse gas emissions and production costs. The integration of precision agriculture with INM further enhances site-specific nutrient management, making it a vital strategy for sustainable agricultural intensification, environmental conservation, and long-term global food security.*

Keywords: *Integrated nutrient management, Crop productivity, Soil health, Biofertilizers, Sustainable agriculture.*

INTRODUCTION

Global food security remains a critical challenge as the world population continues to grow, projected to reach 9.7 billion by 2050. Meeting the increasing food demand requires substantial improvement in agricultural productivity while maintaining environmental sustainability. Soil fertility depletion, caused by intensive cropping, monoculture practices, and indiscriminate use of chemical fertilizers, has emerged as one of the most pressing concerns in modern agriculture (Nayak et al., 2012).

Cite this article: Waghmare, P.K., Vishwakarma, S.K., Sanjivkumar, V., Meena, N.K., Sharma, M.M. (2026). Integrated Nutrient Management for Enhanced Crop Productivity, *Curr. Rese. Agri. Far. 7*(1), 47-55. doi: http://dx.doi.org/10.18782/2582-7146.275

In many agrarian countries, crop yields have either stagnated or declined due to inadequate soil organic matter and deteriorating soil health (Kumar et al., 2023).

Chemical fertilizers, while effective in providing immediate nutrient supply, have been associated with several adverse effects when used excessively. These include soil acidification, nutrient imbalance, groundwater contamination, eutrophication of water bodies, and increased greenhouse gas (GHG) emissions (Wu & Ma, 2015). Furthermore, the declining response of crops to chemical fertilizers alone has necessitated the exploration of alternative and complementary nutrient management strategies that can sustain productivity without compromising environmental integrity (Gruhn et al., 2000).

Integrated Nutrient Management (INM) has emerged as a scientifically validated approach that addresses these challenges by combining organic, inorganic, and biological sources of nutrients in a balanced and synergistic manner. INM refers to the maintenance of soil fertility and plant nutrient supply at an optimum level for sustaining desired crop productivity through optimization of benefits from all possible sources of nutrients in an integrated manner (Janssen, 1993). The INM approach aims to synchronize nutrient demand by the crop with the supply of nutrients from the labile soil pool and applied nutrient sources (Cassman et al., 2002). This review comprehensively examines the concept, components, benefits, and future prospects of INM for enhanced crop productivity and sustainable agriculture.

2. Concept and Principles of INM

Integrated Nutrient Management is a modified nutrient management technique with multifarious benefits, wherein a combination of all possible sources of plant nutrients is used in a crop nutrition package. The INM primarily refers to the judicious, efficient, and integrated use of all available sources of organic, inorganic, and biological components to combine traditional and modern techniques of nutrient management into an environmentally sound and economically optimal agricultural system (Janssen, 1993). The fundamental principles of INM include: (i) optimizing the use of all available nutrient sources; (ii) matching nutrient supply with crop demand in terms of both time and space; (iii) reducing nutrient losses through leaching, runoff, volatilization, and immobilization; and (iv) improving the physical, chemical, biological, and hydrological properties of the soil (Zhang et al., 2012).

The INM system synchronizes the nutrient demand set by plants with the supply of nutrients from the labile soil pool and applied nutrient sources (Cassman et al., 2002). INM encourages the split application of nitrogen fertilizers during critical stages of crop growth in small quantities, which has the potential to increase crop productivity and quality while reducing nutrient losses (Tilman et al., 2002). The approach also promotes methods designed to reduce nutrient losses and enhance plant uptakes, such as the deep placement of fertilizers and the use of nitrification inhibitors or urea coatings (Zhang et al., 2012).

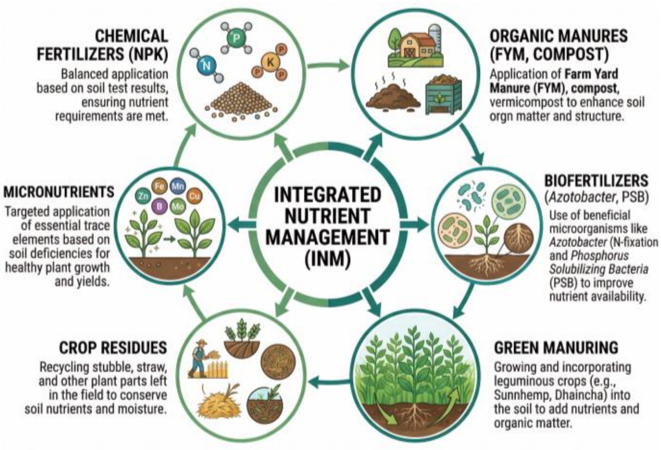

Figure1. Key Components of Integrated Nutrient Management (INM)

3. Key Components of INM

3.1 Chemical Fertilizers

Chemical fertilizers provide readily available nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), which are essential for crop growth. However, only 30–40% of applied nitrogen is typically utilized by the crop, with the remainder lost through various pathways (Jat et al., 2015). INM recommends the balanced and site-specific application of chemical fertilizers based on soil testing and crop requirements. The application of 100% recommended dose of fertilizers (RDF) combined with organic sources has been shown to significantly enhance yields compared to chemical fertilizers alone. Zhang et al. (2012) demonstrated that optimized nitrogen rates using in-season root-zone management reduced N fertilizer use by 60% for wheat and 40% for maize while increasing grain yields by 4–5%. Slow-release and controlled-release fertilizers also contribute significantly to improving nutrient use efficiency by reducing losses and matching nutrient release with crop demand (Nayak et al., 2012).

3.2 Organic Manures and Compost

Organic manures, including farmyard manure (FYM), compost, and vermicompost, form the backbone of INM. They provide a continuous supply of macro- and micronutrients through gradual mineralization, enhance soil organic carbon, improve soil structure, and stimulate microbial activity (Das et al., 2014). Long-term field experiments in India (1973–2004) demonstrated that NPK + FYM treatment showed a statistically significant increase in soybean yield over time, while both control and NPK-alone treatments exhibited declining yield trends (Bhattacharyya et al., 2008). Vermicompost, in particular, has been shown to increase crop yields by 12–140% when combined with chemical fertilizers compared to 100% mineral fertilizer application alone (Shabani et al., 2015). The combined usage of organic manures with chemical fertilizers assures a continuous supply of nutrients by acting as a multi-nutrient pool, with nutrients released slowly during organic matter mineralization (Dwivedi et al., 2016).

3.3 Biofertilizers

Biofertilizers are substances containing living microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere and promote plant growth by increasing the availability of primary nutrients (Vessey, 2003). Key biofertilizers include nitrogen-fixing bacteria (Rhizobium, Azotobacter, Azospirillum), phosphorus-solubilizing bacteria (PSB), and mycorrhizal fungi. Biofertilizers add nutrients through natural processes of nitrogen fixation and phosphorus solubilization, stimulate plant growth through the synthesis of growth-promoting substances, and can increase crop yield by 20–30% while replacing chemical nitrogen and phosphorus by 25% (Bhardwaj et al., 2014). The application of 100% RDF combined with Azotobacter and PSB has been reported to significantly improve nutrient content in both grain and straw, enhance nutrient uptake, and increase available soil NPK levels (Kakraliya et al., 2018). Furthermore, plant growth-promoting rhizobacteria (PGPR) can reduce NP fertilizer use by 25% while improving growth and yield by 29–39% (Thakur et al., 2023).

3.4 Green Manuring and Crop Residues

Green manuring involves the incorporation of leguminous crops such as Sesbania, Crotalaria, and Dhaincha into the soil to enhance nitrogen availability through biological nitrogen fixation. Crop rotations with legumes not only enhance nutrient cycling but also reduce the use of inorganic fertilizers and decrease reactive nitrogen losses from the ecosystem (Peoples et al., 2009). Crop residues, when retained in the field, return nutrients to the soil and improve soil structure, water retention, and microbial activity. The incorporation of crop residues provides substantial amounts of nutrients for succeeding crops and helps immobilize nitrogen initially, followed by gradual mineralization that synchronizes with crop demand (Ambus & Jensen, 2001). INM through green manuring, crop residue incorporation, and other animal-based manures has a profound influence on soil carbon stock and overall soil health (Singh et al., 2009).

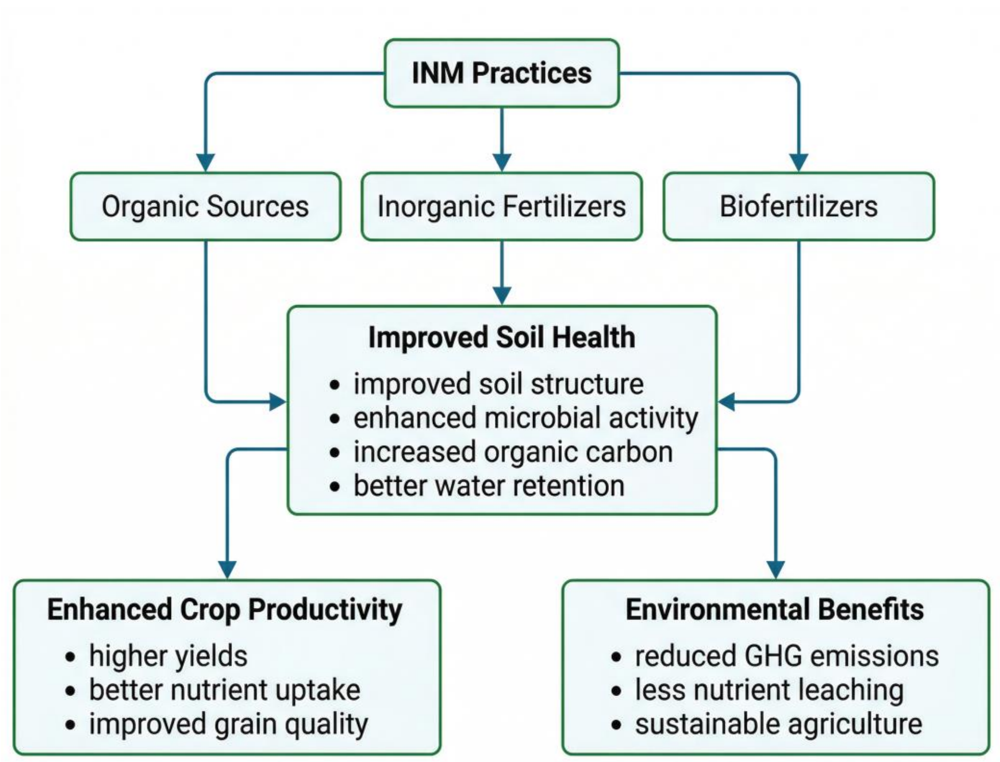

Figure2. Impact of Integrated Nutrient Management on Soil Health and Crop Productivity

4. Effect of INM on Crop Productivity

Numerous studies conducted globally have demonstrated the superiority of INM over conventional nutrient management in enhancing crop yields. Jat et al. (2015) reported that INM enhances crop yields by 8–150% compared with conventional practices, increases water-use efficiency, and improves economic returns to farmers. The increment in crop yields under INM over conventional nutrient management across major cropping systems ranged from 1.3% to 66.5%, with significant improvements observed in field crops, especially rice, wheat, and soybean (Kumar et al., 2023). The combination of NPK with FYM significantly enhanced rice yield by 34–38% compared to chemical fertilizer alone in both wet and dry seasons and also improved energy use efficiency by 13.6–20% (Kakraliya et al., 2018).

In vegetable crops, similar positive effects have been documented. Okra, tomato, and onion crops demonstrated increased yields under INM regimes. The application of 100% RDF combined with vermicompost (10 t/ha) increased rice grain yield by 25% and the harvest index by 9.36% compared to the control treatment (Hoque et al., 2022). In intercropping systems, combining 50% of the recommended dose of nitrogen with 50% nitrogen from vermicompost resulted in the highest chickpea grain yield, outperforming the full RDF application of inorganic NPK fertilizers (Koireng et al., 2022). These findings collectively demonstrate that INM enhances the yield potential of crops over and above what is achievable with recommended chemical fertilizers alone.

5. Effect of INM on Soil Health

INM has a profound positive impact on soil physical, chemical, and biological properties. The integration of organic manures with chemical fertilizers significantly improves soil structure, reduces bulk density, increases porosity, and enhances water-holding capacity compared to the sole use of chemical fertilizers (Hati et al., 2008). Soil organic carbon, a critical indicator of soil health, consistently improves under INM practices. Long-term studies in India showed significant gains in soil organic carbon under intensive cropping systems like rice-wheat, maize-wheat, and maize-mustard when organic manures were combined with inorganic fertilizers (Singh et al., 2009; Nayak et al., 2012).

The biological health of soil is substantially enhanced through INM. Soil microbial biomass carbon (SMBC), a key indicator of microbial activity, increases significantly under integrated nutrient regimes. The continual application of inorganic fertilizers in combination with FYM or lime significantly altered soil microbial biomass carbon, soil nitrogen and phosphorus, fulvic acid, and humic acid (Srinivasarao et al., 2020). Dehydrogenase activity, which reflects overall microbial metabolic activity, also shows marked improvement under INM. Additionally, the inclusion of FYM facilitates the synthesis of humic acid, which subsequently raises the soil organic carbon content and improves nutrient retention capacity (Bajpai et al., 2006). Bio-organic fertilization has been shown to increase soil organic matter by 39%, microbial biomass nitrogen by 32%, and microbial biomass carbon by 27% compared to conventional practices (Reimer et al., 2023).

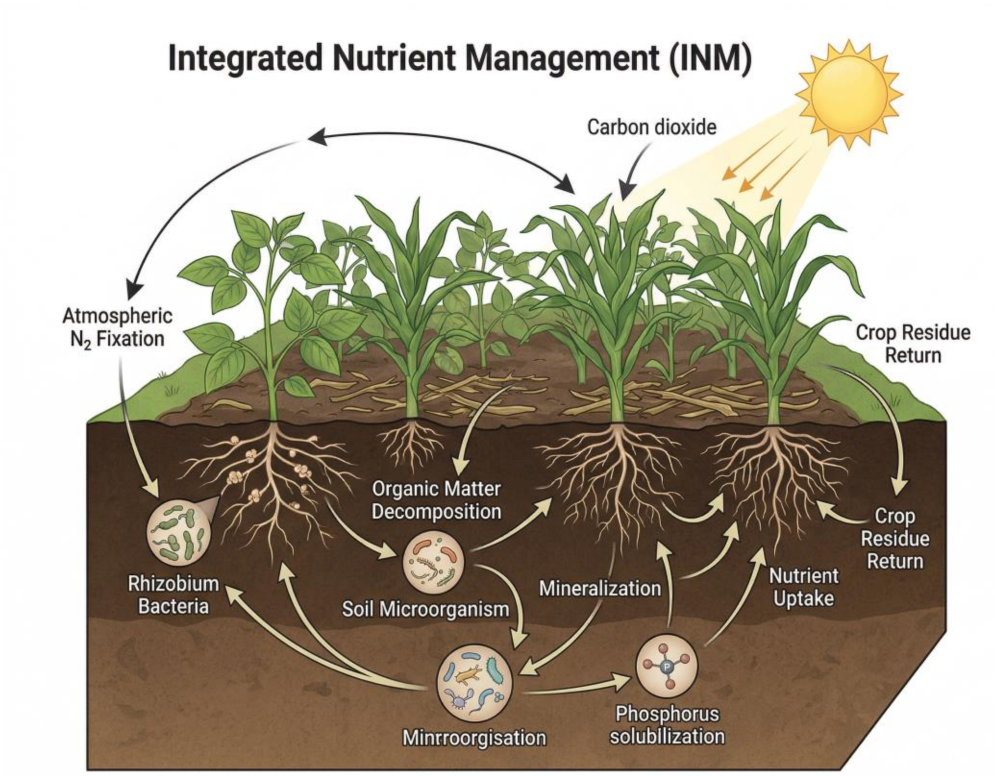

Figure3. Nutrient Cycling Processes in Integrated Nutrient Management Systems

6. Environmental Benefits of INM

INM offers significant environmental benefits by reducing greenhouse gas emissions, nutrient leaching, and overall pollution from agricultural activities. The INM practice in cropped fields showed a substantial reduction in methane emissions over conventional nutrient management (Kumar et al., 2023). Nyamadzawo et al. (2017) reported that practicing INM in maize reduced GHG emissions by approximately 17.1% compared to conventional nutrient management. Another study demonstrated a significant reduction of 1,268% in GHG emissions against conventional nutrient management in the rice-wheat cropping system (Ma et al., 2010). Model simulation and fate assessment further reveal that reactive nitrogen losses and GHG emissions are reduced substantially under advanced INM practices, with lower inputs of chemical fertilizer achieving lower human and environmental costs without compromising crop yields (Jat et al., 2015).

INM promotes high agricultural yields while reducing nitrogen losses and associated detrimental environmental consequences (Gruhn et al., 2000). The deep placement of urea recommended under INM greatly boosts nitrogen-use efficiency with low ammonia volatilization and reduces nitrate leaching (Jambert et al., 1997). The use of nitrification inhibitors further minimizes nitrous oxide emissions (Ju et al., 2011). Furthermore, nutrient recycling and reuse strategies within INM, including composting, biochar production, and anaerobic digestion, convert nutrient-rich waste materials into valuable organic amendments, thereby promoting circular nutrient economy in agriculture (Kumar et al., 2023).

7. Comparative Benefits of INM

Table1. Comparative Benefits of INM over Conventional Nutrient Management

Parameter	Effect of INM	Reference
Crop Yield Enhancement	8–150% increase over conventional	Jat et al. (2015)
Soil Organic Carbon	Significant increase under long-term INM	Singh et al. (2009)
Microbial Biomass Carbon	27–32% increase with bio-organic inputs	Reimer et al. (2023)
GHG Emission Reduction	17.1% reduction in maize systems	Nyamadzawo et al. (2017)
Nitrogen Use Efficiency	28% higher with site-specific management	Nayak et al. (2012)
Water-Use Efficiency	Improved with organic + inorganic inputs	Jat et al. (2015)
Bulk Density Reduction	Lower BD in top 30 cm soil layers	Hati et al. (2008)

8. Future Perspectives

The future of INM lies in the integration of advanced technologies with traditional nutrient management practices. Precision nutrient management, employing remote sensing, geospatial analysis, and machine learning algorithms, can assess crop nutrient requirements at a fine-scale level and deliver precise, site-specific nutrient applications (Kumar et al., 2023). Site-specific nutrient management (SSNM) has already demonstrated significant improvements in rice and maize yields by 24% and 69%, respectively, compared to traditional farmer practices (Nayak et al., 2012). Furthermore, microbial interventions using mycorrhizal fungi, rhizobacteria, and other plant growth-promoting microbes offer promising avenues for improving nutrient availability, uptake efficiency, and crop productivity. The development of nano-fertilizers and biochar-based amendments also holds potential for enhancing nutrient delivery and soil carbon sequestration within INM frameworks.

CONCLUSION

Integrated Nutrient Management represents a paradigm shift in modern agriculture, offering a comprehensive, scientifically validated, and environmentally sustainable approach to crop nutrition. The extensive body of research reviewed in this paper demonstrates that INM consistently outperforms conventional nutrient management across multiple parameters, including crop yield (8–150% enhancement), soil organic carbon, microbial biomass, nutrient use efficiency, and greenhouse gas emission reduction. The synergistic combination of organic manures, chemical fertilizers, biofertilizers, green manures, and crop residues creates a balanced and dynamic nutrient matrix that sustains crop productivity while preserving long-term soil health and environmental quality.

INM not only addresses the immediate nutritional needs of crops but also contributes to soil carbon sequestration, enhanced microbial diversity, improved water-holding capacity, and reduced environmental pollution.

The integration of precision agriculture technologies with INM further offers promising opportunities for optimizing nutrient delivery and minimizing losses. As the global agricultural community confronts the dual challenges of feeding a growing population and mitigating climate change, the widespread adoption of INM emerges as an indispensable strategy for achieving sustainable agricultural intensification, long-term food security, and environmental stewardship. Policy support, farmer education, and continued research investment are essential to facilitate the broader adoption and refinement of INM practices across diverse agroecological zones and cropping systems worldwide.

Acknowledgements:
The authors appreciate the collaborative efforts of all co-authors in successfully completing this study.

Funding:
No financial support was received.

Conflict of Interest:
The authors declare no conflicts of interest.

Author Contributions:
All authors contributed equally to the manuscript preparation and approval.

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