



## Impact of integrated nutrient management on crop yield, soil health, and sustainability

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### Abstract

Consequently, this essay examines Integrated Nutrient Management (INM) as a coordinated approach that combines organic amendments, mineral fertilizers, biofertilizers, and site-specific diagnostics to meet crop nutrient demands while maintaining ecological balance. INM is defined here as the planned integration of diverse nutrient sources and decision tools to optimize timing, placement, and quantity, thereby aligning productivity goals with resource stewardship. The analysis considers how INM improves crop yield through balanced nutrient supply, improved nutrient-use efficiency, and greater resilience to climatic and edaphic variability. It also evaluates effects on soil health, including organic matter dynamics, biological activity, aggregation, and nutrient cycling, which underpin sustained fertility across seasons. Beyond field performance, the discussion addresses environmental and economic sustainability by assessing reductions in nutrient losses, mitigation of greenhouse gas emissions, input-use efficiency, and cost stability for farmers, setting the stage for evidence-based evaluation across yield, soil, and sustainability outcomes.

**Keywords:** Integrated nutrient management (inm), crop productivity, soil fertility, sustainable agriculture and nutrient use efficiency

### Introduction

Moreover, Integrated Nutrient Management (INM) refers to the coordinated use of organic inputs, mineral fertilizers, biological inoculants, and diagnostic tools to supply nutrients in synchrony with crop demand. It has gained relevance in modern agriculture as production systems contend with finite fertilizer resources, climate variability, and the need to curtail nutrient losses that degrade water quality and air. By aligning timing, placement, and nutrient forms, INM aims to sustain yields while maintaining soil processes that support long-term productivity and buffering capacity. The approach is operationally flexible, allowing site-specific combinations that respond to soil constraints, cropping sequences, and local resource availability without sacrificing agronomic rigor. This essay examines three connected domains: first, the effects of INM on crop yield through balanced supply and improved nutrient-use efficiency; second, the influence on soil health via organic matter turnover, aggregation, and biotic activity; and third, environmental and economic sustainability outcomes associated with reduced losses and steadier input costs.

### Understanding Integrated Nutrient Management

Furthermore, Integrated Nutrient Management (INM) is the deliberate coordination of organic materials, mineral fertilizers, and biological agents to match crop demand across time and space while maintaining soil functions. Its principles include balancing nutrient budgets, synchronizing release with phenological stages, and using diagnostics to guide rate, source, timing, and placement, thereby aligning agronomic goals with environmental safeguards (Selim, 2020) [15, 16]. Core components span composts, manures, crop residues, green manures, and cover crops that build organic carbon, alongside mineral inputs targeted to specific deficiencies identified through soil testing, and microbial

inoculants such as mycorrhizae and nitrogen-fixing bacteria that improve acquisition and cycling (Kushwah *et al.*, 2024) [10]. The rationale for integration rests on complementarity: organic inputs improve structure, water retention, and microbial activity, while mineral sources provide immediately available nutrients that prevent shortfalls during peak demand, and inoculants strengthen rhizosphere interactions. In practice, crop rotation and diversification extend these gains by distributing nutrient extraction, disrupting pest cycles, and stabilizing soil fertility across seasons (Kushwah *et al.*, 2024) [10].

Furthermore, nutrient management practices trace a trajectory from nutrient recycling in traditional mixed farming to the standardized use of synthetic fertilizers during the Green Revolution, and finally toward integration as limitations of single-source approaches became apparent. Early systems relied on manures, composts, and legume rotations that sustained soil organic matter but could not always meet rapidly increasing nutrient demand under intensified cropping. The widespread adoption of mineral fertilizers delivered immediate yield gains, yet imbalances in nutrient ratios, declining soil biological activity, and externalities such as runoff prompted recalibration of practice and policy. In response, INM emerged by recombining organic amendments, targeted chemical inputs, and biofertilizers with diagnostic tools, thereby linking short-term nutrient availability to long-term soil function and system resilience (Panta & Parajulee, 2021) [11]. This historical shift reflects a pragmatic synthesis: integration reduces exclusive dependence on chemical inputs while improving microbial activity and soil properties that support stable productivity across seasons (Panta & Parajulee, 2021) [11].

Additionally, common strategies within Integrated Nutrient Management include crop rotation, which distributes

nutrient extraction across species and phases, and green manuring, where leguminous cover crops fix nitrogen and supply labile carbon that supports microbial turnover. Composting stabilizes organic residues into humified fractions that release nutrients gradually while improving aggregation and water retention, thereby moderating seasonal variability in nutrient supply. The use of biofertilizers—such as rhizobia, *Azotobacter*, phosphate-solubilizing bacteria, and arbuscular mycorrhizae—enhances nutrient acquisition pathways and can reduce dependence on mineral inputs during critical growth stages. Operationally, these techniques are linked through diagnostics that align nutrient release with phenology and through decision support that coordinates application timing, residue management, and inoculant viability, mirroring integrated decision cycles adopted in adjacent agricultural management frameworks (Dara, 2019) [4]. Moreover, farmer training and information-sharing networks sustain the continuity of these practices by standardizing protocols for compost maturity, inoculant quality control, and rotation planning, thereby improving field-level consistency and scaling across production systems (Dara, 2019) [4].

### Impact of INM on Crop Yield

Consequently, empirical comparisons across crops indicate that Integrated Nutrient Management consistently raises yields relative to mineral-only fertilization through complementary supply and synchronized release. A meta-level review reports yield gains from 1.3% to 66.5% in rice, wheat, and soybean under INM, attributed to improved nutrient availability and better soil physical conditions that support root growth and water capture (Paramesh *et al.*, 2023) [12]. Field-level evidence in maize grown on acid Inceptisols shows that combining NPK with farmyard manure or vermicompost, biofertilizers, and liming improves root density and nutrient uptake, with lime serving as an essential amendment to correct acidity constraints (Ghosh *et al.*, 2019) [6, 7]. Notably, plots receiving chemical fertilizer without an organic component suffered a 53% yield reduction, highlighting the risk of nutrient imbalances and poor rhizosphere function when rapid-release sources are used alone (Ghosh *et al.*, 2019) [6, 7]. Together, these findings show that integrated packages outperform conventional programs by aligning immediate nutrient supply with sustained soil-mediated support for growth (Paramesh *et al.*, 2023) [12].

Moreover, the productivity gains observed under Integrated Nutrient Management arise from process-level improvements in nutrient solubility, rhizosphere transport, and root acquisition efficiency. Organic amendments supply labile carbon and functional groups that chelate cations and buffer pH, increasing the availability of phosphorus, micronutrients, and ammonium while improving water retention that supports mass flow to roots (Kushwah *et al.*, 2024) [10]. Concurrently, mineral fertilizers targeted by soil testing prevent transient deficits during peak demand, ensuring adequate ionic gradients for uptake and reducing antagonisms that occur when single nutrients are applied without balance (Kushwah *et al.*, 2024) [10]. Biofertilizers strengthen these effects: mycorrhizal hyphae extend the depletion zone and accelerate phosphorus and zinc uptake, whereas nitrogen-fixing and phosphate-solubilizing bacteria contribute ammonium and mobilized orthophosphate,

thereby lowering the energetic cost of acquisition. Finally, crop rotation and cover crops maintain continuous nutrient cycling and root exudation, preserving microbial biomass and enzyme activity that sustain mineralization across seasons and stabilize supply during critical phenological stages (Kushwah *et al.*, 2024) [10].

In addition, optimal yield responses under Integrated Nutrient Management arise when nutrient supply is balanced across macronutrients and micronutrients while simultaneously curbing pathways of loss such as leaching, volatilization, and runoff. Balancing sources through calibrated combinations of organic and mineral inputs aligns supply with crop demand, preventing antagonisms and hidden hunger that depress photosynthate allocation to grain; concurrently, organic amendments increase cation exchange capacity and moisture retention, moderating concentration peaks that otherwise drive nitrate movement beyond the root zone (Chejara *et al.*, 2021) [2, 3]. Reduced losses maintain a steadier root-zone concentration, sustaining uptake kinetics during critical phenophases and preserving energy for growth rather than stress responses associated with deficiency-surplus cycles. Moreover, recycling on-farm residues and manures supplies slowly mineralizing pools that dampen temporal variability and decrease reliance on high single-dose applications, which are more prone to gaseous and hydraulic export from fields (Chejara *et al.*, 2021) [2, 3]. These dynamics translate into higher agronomic efficiency, allowing lower applied doses to deliver comparable or greater yield through improved recovery and conversion.

For example, multi-season field trials in acidic Inceptisols showed that maize receiving a coordinated package of NPK, farmyard manure or vermicompost, biofertilizers, and lime produced higher ear length, kernels per row, and grain yield than mineral-only controls, indicating that integration corrected both nutrient supply and edaphic constraints (Ghosh *et al.*, 2019) [6, 7]. The inclusion of lime was decisive because it improved rhizosphere pH and exchange sites, which, together with organic inputs, raised root density and sustained uptake during peak demand phases (Ghosh *et al.*, 2019) [6, 7]. Notably, the same experiments reported a 53% yield reduction where chemical fertilizers were applied without any organic amendment, demonstrating that unbuffered soluble inputs can depress performance in low-buffer soils even when nominal nutrient rates are adequate (Ghosh *et al.*, 2019) [6, 7]. These outcomes align with the preceding process analysis by linking yield gains to synchronized availability, moderated loss pathways, and improved root-soil contact. They also provide a template for rice-wheat systems on marginal soils, where calibrated liming and organic additions can stabilize returns while maintaining fertilizer response.

However, consistent yield gains under Integrated Nutrient Management are not guaranteed because variability in the quality and decomposition rate of organic materials can desynchronize nutrient release from crop demand, especially under fluctuating moisture and temperature. Heterogeneous carbon-to-nitrogen ratios, variable lignin content, and uncertain microbial activity alter mineralization trajectories, requiring frequent calibration of mineral supplements to avoid temporary deficits or surpluses during peak uptake. Labor and management demands also constrain outcomes: composting, residue handling, and properly timed applications add seasonal workload that smallholders may

not meet during critical windows, thereby reducing the effectiveness of synchronized supply. Moreover, limited extension support, uncertain access to reliable inoculants, and fragmented markets for quality organic inputs create input inconsistency and risk that discourage sustained adoption and learning-by-doing needed to refine site-specific protocols (Tiemann & Douxchamps, 2023) [17]. These technical and institutional constraints interact with cost structures and price signals, so that even agronomically sound packages may not be implemented at scale without supportive research, financing, and market arrangements (Tiemann & Douxchamps, 2023) [17].

### **Influence of INM on Soil Health**

Meanwhile, Integrated Nutrient Management (INM) improves soil fertility by building organic matter pools that support aggregate stability, pore continuity, and water retention, thereby creating conditions that sustain nutrient availability across seasons (Selim, 2020) [15, 16]. The combined application of organics with calibrated mineral fertilizers and biofertilizers increases soil organic carbon and cation exchange capacity, moderates acidity through liming, and raises base saturation, which together strengthen nutrient buffering and reduce transient deficits (Ghosh *et al.*, 2019) [6, 7]. Enhanced structure and higher water-holding capacity lower bulk density and improve aeration, facilitating microbial turnover that drives mineralization of nitrogen and mobilization of phosphorus and micronutrients into plant-available forms (Ghosh *et al.*, 2019) [6, 7]. These biological feedbacks are reinforced as organic inputs supply energy substrates for microbes, allowing steady enzyme activity and rhizosphere interactions that maintain cycling even under variable moisture and temperature (Selim, 2020) [15, 16]. Consequently, INM creates a self-reinforcing soil system in which physical quality, microbial processes, and chemical reserves jointly sustain fertility and stabilize crop response.

Furthermore, Integrated Nutrient Management stimulates soil microbial activity and biodiversity by supplying diverse carbon substrates and habitat structure through organic amendments while providing targeted mineral nutrients that prevent metabolic bottlenecks. Manures, composts, and residue incorporation increase particulate and dissolved organic matter, fueling heterotrophic growth and enzyme production, whereas improved aggregation and porosity protect microbial microhabitats from desiccation and predation, supporting a richer assemblage of decomposers, mutualists, and nitrifiers (Paramesh *et al.*, 2023) [12]. Biofertilizers add functional groups such as rhizobia, *Azotobacter*, phosphate-solubilizing bacteria, and arbuscular mycorrhizae, which expand nutrient acquisition pathways, intensify rhizosphere signaling, and create complementary niches that stabilize community structure during seasonal fluctuations. These interactions reduce the amplitude of nutrient oscillations by coupling mineralization to crop phenology, thereby maintaining steady root-zone availability while lowering the risk of opportunistic blooms associated with unbalanced inputs (Paramesh *et al.*, 2023) [12]. As a result, microbial biomass, diversity, and activity co-vary with improved physical conditions and carbon supply, strengthening nutrient cycling, resilience to stress, and long-term soil function.

As a result, the integrated use of organic amendments, biofertilizers, and calibrated mineral inputs reduces soil

degradation by improving aggregation and cation exchange capacity, which curtails crusting, compaction, and surface sealing that precede erosive losses (Panta & Parajulee, 2021) [11]. Compared to exclusive chemical fertilization, INM builds soil organic carbon and microbial biomass that strengthen aggregate stability and pore continuity, thereby lowering runoff velocity and sediment detachment on sloping and intensively tilled fields (Panta & Parajulee, 2021) [11]. Increased biological activity also accelerates residue decomposition into stable fractions, raising water infiltration and moisture retention, which in turn dampens erosive episodes during high-intensity rainfall. Concurrently, balanced nutrient supply and improved buffering reduce nutrient depletion by maintaining root-zone availability and moderating leaching and volatilization that occur under high, unbalanced soluble applications. Evidence from synthesis work indicates that these physical and biological gains coincide with improved chemical status, producing fields that retain nutrients longer and lose less soil mass than systems reliant on mineral fertilizers alone (Panta & Parajulee, 2021) [11].

Additionally, Integrated Nutrient Management stabilizes soil pH and mitigates salinity and toxicity by coordinating organic inputs, targeted mineral amendments, and microbial inoculants to regulate ionic balances and buffering capacity. Organic materials contribute functional groups and carbonate equivalents that neutralize acidity, increase cation exchange capacity, and complex aluminum and manganese, thereby reducing root toxicity while moderating rapid shifts that follow heavy soluble fertilizer use (Kushwah *et al.*, 2024) [10]. Where sodicity or salinity pressures exist, gradual nutrient release from composts and manures lowers osmotic stress, while balanced mineral additions avoid sodium accumulation by maintaining adequate calcium, magnesium, and potassium on exchange sites to sustain flocculation and infiltration. Biofertilizers, including mycorrhizae and nitrogen-fixing bacteria, improve nutrient uptake efficiency at moderate concentrations, allowing lower salt loads per unit yield and reducing the frequency of high-conductivity applications that destabilize pH and induce ion antagonisms (Kushwah *et al.*, 2024) [10]. In turn, crop rotation and diversification distribute extraction patterns, limit chloride and sodium carryover, and permit periodic corrective liming or gypsum scheduling to maintain favorable reaction conditions across seasons.

### **Environmental and Economic Sustainability of INM**

Consequently, Integrated Nutrient Management (INM) delivers environmental gains by aligning nutrient inputs with crop demand, which curtails surplus nitrogen and phosphorus prone to leaching and runoff into waterways. By substituting portions of synthetic fertilizers with organic sources and calibrating mineral applications, INM decreases reactive nitrogen accumulation, a change linked to lower nitrous oxide and nitric oxide emissions and improved yield-scaled emission intensity in rice systems managed with ground cover and water-saving practices (Yao *et al.*, 2018) [18]. Reduced emission factors in these systems indicate that synchrony and source blending diminish gaseous losses while sustaining grain output, thereby limiting atmospheric pollution without compromising production (Yao *et al.*, 2018) [18]. Parallel gains arise from recycling agricultural wastes into composts and manures, which replaces external inputs, stabilizes soil structure that

retains nutrients, and lowers pollution risk, while also reducing total nutrient costs for farmers through on-farm resource use (Chejara *et al.*, 2021) <sup>[2, 3]</sup>. These adjustments support ecosystem services by improving soil carbon stocks, water infiltration, and microbial functioning that regulate nutrient cycling (Chejara *et al.*, 2021) <sup>[2, 3]</sup>.

Moreover, the economic case for Integrated Nutrient Management (INM) rests on reduced expenditure for mineral fertilizers through partial substitution with on-farm organics and improved nutrient-use efficiency that lowers application rates without depressing output. Input cost savings are reinforced when calibrated blends avert quality penalties—especially in fruit systems where excess inorganic fertilization reduces marketable grade and price—thereby protecting revenue streams while maintaining agronomic performance (Kumari, 2025) <sup>[9]</sup>. Yield stability adds further value by smoothing interseasonal variability, since gradual nutrient release from composts and manures sustains uptake during weather fluctuations, reducing the risk of shortfalls that trigger emergency purchases or lost sales. These effects compound over time as soil carbon, cation exchange capacity, and microbial activity strengthen recovery efficiency, enabling smaller incremental doses to achieve target yields and lowering the cost per unit of production. Consequently, multi-year profitability improves through a combination of lower variable costs, steadier yields, and reduced postharvest losses linked to more consistent product quality and size distributions (Kumari, 2025) <sup>[9]</sup>.

Furthermore, the scalability and adaptability of Integrated Nutrient Management (INM) arise from its modular design, which allows tailored blends of organic materials, mineral fertilizers, and biofertilizers to match resource endowments and climatic constraints across agro-ecological zones. In rainfed semi-arid systems, priority can be given to composts and residue mulches that improve water retention and buffer nutrient release, while targeted mineral supplements address episodic deficits during short, intense growing periods (Selim, 2020) <sup>[15, 16]</sup>. In irrigated rice–wheat belts, synchronized dosing guided by diagnostics can integrate manures and green manures to stabilize soil structure, with calibrated mineral inputs maintaining yield targets under high-cropping intensity (Selim, 2020) <sup>[15, 16]</sup>. Smallholders can rely on on-farm residues and seasonal legume covers to reduce cash expenditures, whereas commercial farms can deploy precision placement and quality-controlled inoculants to improve recovery efficiency within mechanized schedules. Policy and extension frameworks further support scaling by standardizing testing services, compost quality benchmarks, and training that translate INM principles into locally actionable protocols for diverse farming systems.

In addition, Integrated Nutrient Management (INM) contributes to climate change mitigation by increasing soil organic matter and microbial activity that support carbon stabilization while lowering emission intensity through improved nutrient-use efficiency. Long-term INM in acidic Inceptisols raised dehydrogenase and phosphomonoesterase activities and increased soil organic matter, conditions that favor carbon accrual in aggregates and reduce the need for high mineral fertilizer doses associated with nitrous oxide release (Patra *et al.*, 2020) <sup>[13]</sup>. These biophysical changes complement adaptation by improving water-holding capacity, aggregation, and root-zone nutrient buffering,

which sustain crop performance during drought and high-rainfall variability common under shifting climates. Moreover, diversified nutrient sources and biofertilizers expand acquisition pathways, allowing crops to maintain uptake at moderate concentrations, thereby reducing osmotic stress and the probability of loss spikes during extreme events while preserving yield stability. By strengthening microbial-mediated cycling and maintaining a steadier nutrient supply, INM builds soil functions that both sequester carbon and buffer production risks under climate uncertainty (Patra *et al.*, 2020) <sup>[13]</sup>.

### Barriers and Challenges to INM Adoption

Nevertheless, widespread adoption of Integrated Nutrient Management (INM) is constrained by intertwined knowledge, resource, and policy obstacles that vary across farm types and infrastructure contexts. Surveys indicate that both adopters and nonadopters experience barriers, including uncertainty about performance, limited time for learning, and administrative burdens linked to compliance or documentation, suggesting that motivation alone does not remove adoption frictions (Rudnick *et al.*, 2023) <sup>[14]</sup>. Resource constraints remain pronounced: smaller farms face cash-flow limits for composting equipment, testing services, and quality inoculants, whereas larger parcels with microirrigation and advisory networks are more likely to implement practices such as split applications and ET-based scheduling that support INM's synchrony objectives (Khalsa *et al.*, 2022) <sup>[8]</sup>. Information bottlenecks further impede progress when field-relevant guidance is not delivered through trusted local channels, making extension and pest control advisors crucial conduits for context-specific diagnostics and scheduling. Finally, policy frameworks that reward yield but not nutrient-use efficiency, and fragmented quality standards for organics, weaken incentives to coordinate sources and timing at scale (Rudnick *et al.*, 2023) <sup>[14]</sup>.

To address these challenges, a coordinated policy package should combine strengthened extension services, targeted subsidies, and iterative farmer training that builds decision capacity and confidence. Extension programs need to deliver site-specific diagnostics, split-application scheduling, and quality standards for composts and inoculants while engaging trusted advisors, since adoption is shaped by perceived efficacy and social learning processes central to behavior change (Gao & Arbuckle, 2021) <sup>[5]</sup>. Subsidies should reduce upfront costs for soil testing, composting infrastructure, lime, and biofertilizers, and be structured as performance-based incentives that reward nutrient-use efficiency and verified reductions in loss pathways rather than volume of inputs applied. Training curricula ought to develop self-efficacy through hands-on trials, peer mentoring, and decision tools that reflect local rotations and risk profiles, with modules attuned to age, acreage, insurance participation, and economic pressure that predict adoption heterogeneity (Gao & Arbuckle, 2021) <sup>[5]</sup>. Finally, policy alignment across crop insurance, procurement, and environmental compliance can link premium discounts and market access to documented INM plans and monitoring, reinforcing durable practice change.

### Future Prospects and Innovations in INM

Subsequently, future Integrated Nutrient Management will be shaped by precision tools that align nutrient release with

rapidly shifting field conditions, reducing exposure to weather-driven yield volatility. Variable-rate application guided by proximal sensors and satellite imagery can tailor nitrogen and phosphorus to canopy status and soil heterogeneity, while closed-loop controllers coordinate split doses with evapotranspiration and soil moisture dynamics. Digital monitoring systems that combine in situ ion-selective probes, low-cost spectrometry, and machine learning can forecast short-term nutrient deficits and recommend adjustments prior to stress, a capability that is especially relevant as temperature and precipitation extremes depress yields in many regions (Beillouin *et al.*, 2020) <sup>[1]</sup>. Novel biofertilizers—engineered consortia of mycorrhizae, diazotrophs, and phosphate-mobilizers—paired with carriers that protect viability during storage and field fluctuations could maintain acquisition pathways when heat or drought constrains mineralization (Beillouin *et al.*, 2020) <sup>[1]</sup>. Finally, decision platforms integrating weather nowcasts, seasonal outlooks, and crop models would schedule amendments to avoid loss-prone windows, improving nutrient-use efficiency and resilience.

Finally, advancing Integrated Nutrient Management (INM) requires sustained research programs that co-develop site-specific protocols with farmers while generating comparative evidence on yield stability, nutrient-use efficiency, and soil recovery under diverse constraints. Public research should prioritize long-term trials that quantify decomposition dynamics of local organics, performance of biofertilizers in variable climates, and cost-benefit profiles that reflect labor peaks and market volatility, thereby reducing uncertainty that currently dampens adoption (Tiemann & Douxchamps, 2023) <sup>[17]</sup>. Education and extension must translate these findings into modular training on diagnostics, split applications, compost quality control, and inoculant handling, delivered through trusted local advisors and peer networks that support iterative learning and adaptive management. International cooperation can align funding with problem-driven research, harmonize compost and inoculant standards, and revise trade rules to recognize the additional costs of sustainability-focused management, fostering cross-border diffusion of validated INM packages (Tiemann & Douxchamps, 2023) <sup>[17]</sup>. Together, these actions build credible evidence, stable incentives, and institutional capacity needed for durable, large-scale uptake.

## Conclusion

Altogether, the evidence presented shows that Integrated Nutrient Management (INM) raises crop yield by synchronizing nutrient supply with phenology, aligning immediate mineral availability with the structural and biological support derived from organics and biofertilizers. This coordinated strategy stabilizes soil health through increases in organic carbon, improved aggregation, higher cation exchange capacity, and resilient microbial communities that maintain mineralization and nutrient buffering across seasons. Environmental outcomes follow from reduced leaching, volatilization, and runoff, alongside lower emission intensity and greater carbon retention, while economic performance improves through reduced input requirements, steadier yields, and protection of product quality. Although adoption faces knowledge, infrastructure, and policy barriers, modular design and precision tools demonstrate a feasible path for scaling across farm sizes and

agro-ecologies. Therefore, INM stands as a practical foundation for future agriculture by coupling productivity with resource stewardship, offering a durable route to maintain food supply while safeguarding soils and minimizing externalities.

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