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Sustainable integrated nutrient management in horticultural and vegetable crops: Mechanisms, innovations, and global food security: A review

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Abstract

Global food security is increasingly threatened by population growth, climate change, soil degradation, and inefficient nutrient management. Conventional reliance on chemical fertilisers alone has led to reduced soil fertility, inefficient nutrient use, environmental degradation, and financial difficulties for farmers. A sustainable method of increasing agricultural yield while restoring soil health and lessening environmental effects is Integrated Nutrient Management (INM), which carefully blends organic, inorganic, and biological nutrient sources. In addition to addressing mechanistic insights into nutrient absorption, translocation, and utilization efficiency, this review critically synthesizes current research on INM. It also highlights recent technical advancements, including microbial inoculants, improved fertilisers, and precision agriculture technologies. INM enhances yield stability, fertilizer usage efficiency, with special emphasis on horticultural and vegetable production systems. and long-term soil sustainability, according to data from horticultural and agronomic systems in various agroecological areas. Along with highlighting the integration of mechanistic understanding with useful and policy-relevant solutions, the study also reveals important knowledge gaps, adoption barriers, and research objectives. This analysis offers a thorough framework for improving INM as a pillar for resilient global food systems and sustainable agriculture by connecting basic processes with applied advances.

Keywords: Integrated nutrient management, sustainable agriculture, nutrient use efficiency, soil health, precision agriculture, organic fertilizers, inorganic fertilizers, climate-smart agriculture, balanced fertilization

1. Introduction

1.1 Global challenges in nutrient management under intensive and climate-stressed agriculture

Over the next forty years, it is anticipated that the world's population will grow by around 35%^[1]. Global crop consumption is expected to almost double by the middle of the century due to rapid population increase and dietary changes, yet the development of arable land is severely limited, necessitating further intensification of production on current croplands^[2, 3]. Synthetic fertilizers and other inputs, which today make up at least 40–50% of the world's food supply, have been crucial to intensification during the past several decades. However, this has also resulted in significant nutritional imbalances and environmental externalities^[4, 5]. Due to restricted access to organic amendments and mineral fertilizers, smallholder farming systems in sub-Saharan Africa, parts of Latin America, and Asia continue to suffer from chronic nutrient depletion, which leads to consistently low yields and increasing soil degradation^[6, 7]. On the other hand, extensive nitrogen (N) and phosphorus (P) surpluses are found in intensive systems in North America, Europe, China, and portions of South and East Asia. Overuse of these systems causes nitrate leaching, eutrophication, greenhouse gas emissions, and disruption of the N:P stoichiometry in terrestrial and aquatic ecosystems^[8]. By altering soil moisture, redox conditions, and microbial activity, climate variability and change such as warming, altered precipitation regimes, droughts, and extreme rainfall are reshaping nutrient cycling,

mineralization, and loss pathways on top of these structural imbalances. These changes have been shown to have an impact on the availability of N, P, K, and micronutrients as well as the nutritional quality of crops ^[9]. Increased atmospheric CO₂ levels and heat can change the protein and mineral content of grains, decrease plant nutrient absorption efficiency, and combine with hydrological extremes to increase nutrient losses through erosion, volatilization, and leaching ^[9, 10]. These interconnected stresses result in several geographical issues: Nutrient-limited, rainfed smallholder systems, particularly in Africa and South Asia, face declining land availability per capita, persistent yield gaps, and increased vulnerability to climate shocks, while high-input, irrigated, and specialized livestock-cropping systems must reduce legacy nutrient surpluses and increase nutrient circularity without sacrificing productivity ^[10, 11]. Together, these patterns characterize a worldwide nutrient management issue where food security, environmental integrity, and the adaptability of smallholder and intensive systems to climate change are all at risk from both excess and deficiency.

1.2 Declining soil fertility, low nutrient use efficiency, and environmental externalities

Low nutrient use efficiency (NUE) and declining soil fertility are two of the main causes of environmental deterioration in contemporary agriculture. Long-term reductions in soil productivity and resilience have resulted from intensive tillage, residue clearance, uneven fertilization, erosion, and increased losses of soil organic carbon (SOC), nutrient depletion, acidification, and salinization ^[12, 13]. Reduced SOC increases the need for mineral fertilizers by reducing the availability of organically bound nutrients and weakening the soil's buffering capabilities. While comparable inefficiencies impact phosphorus and potassium owing to fixation and soil limits, the worldwide crop recovery of applied nitrogen is still low (around 25-50%), with significant losses through leaching, volatilization, runoff, and denitrification ^[14]. Increased greenhouse gas emissions, eutrophication of aquatic ecosystems, and groundwater nitrate pollution are all directly caused by these processes, which reinforce a feedback loop where low NUE and diminishing soil fertility raise environmental externalities and input reliance.

1.3 Nutrient management, food security, and alignment with the sustainable development goals

Beyond a limited focus on fertilizer inputs, nutrient management is a key factor in determining food security and a major force behind advancement toward several Sustainable Development Goals (SDGs) ^[15]. In order to close yield gaps, improve crop nutritional quality, and guarantee stable access to sufficient and nutritious food, especially in nutrient-deficient regions, adequate and effective management of nitrogen (N), phosphorus (P), potassium (K), and micronutrients is crucial. This directly supports SDG 2 (Zero Hunger) ^[16]. The use of fertilizer and integrated nutrient management (INM) may boost agricultural yields by 8-150% and enhance nutritional quality by around 12%, highlighting their crucial role in food supply and nutrition ^[17]. Additionally, nutrient management helps achieve SDG 12 through increased nutrient circularity, decreased waste, recycling from secondary nutrient streams, and improved nutrient use efficiency (NUE) ^[18]; SDG 13 by reducing greenhouse gas emissions, especially N₂O, linked to inefficient fertilizer use ^[19]; and SDG 15 by reducing eutrophication, soil degradation, and biodiversity loss through balanced fertilization and soil conservation ^[20]. Increasing yields on current agricultural land while separating production from nutrient

losses is the foundation of sustainable intensification. This may be accomplished through INM, site-specific nutrient management, diverse and legume-inclusive cropping systems, and circular nutrient fluxes. Higher NUE does not reduce production, according to evidence from long-term studies and meta-analyses; rather, optimal nutrition methods frequently increase yield stability while lowering environmental concerns. As a result, responsible plant nutrition, nutrient budgeting, 4R stewardship, and sustainability-focused national nutrient roadmaps are becoming increasingly important global policy tools for transforming agri-food systems within planetary boundaries and in line with the SDG framework ^[21].

1.4 Limitations of conventional fertilizer-centric approaches

Agronomic, economic, and environmental constraints are rapidly limiting conventional fertilizer-centric farming systems. Despite ongoing increases in nitrogen, phosphate, and potassium inputs, fertilizer application has increased more quickly than crop yields in many intensive production locations, leading to falling marginal returns, low nutrient usage efficiency, and the formation of yield plateaus ^[22]. Widespread nutrient imbalances have resulted from an over-reliance on nitrogen and, in certain systems, phosphorus together with insufficient replenishment of potassium, sulfur, and micronutrients. This has decreased fertilizer efficiency and contributed to "hidden hunger" in soils and crops ^[23]. By reducing soil organic matter, weakening soil structure, acidifying soils, and suppressing beneficial microbial communities, long-term domination of mineral fertilizers without enough organic inputs further deteriorates soil health and compromises resilience and production ^[24]. Farmers, especially in low-income areas, face increased production costs and financial risk due to rising fertilizer prices, which are intimately connected to energy markets and geopolitical instability ^[25]. Additionally, over application reduces profitability without corresponding yield benefits ^[26]. Stricter rules on the use of phosphorus and nitrogen have been implemented in many nations as a result of increased environmental externalities caused by nutrient losses to water bodies and the atmosphere ^[27]. When taken as a whole, these limitations demonstrate the shortcomings of fertilizer-centric techniques as a stand-alone route for sustainable intensification and emphasize the necessity of integrated, efficiency-focused, and soil-health-based nutrient management solutions.

1.5 Integrated nutrient management (INM) as a 'system-based solution'

Integrated Nutrient Management (INM) represents a comprehensive approach that synergistically combines organic and inorganic nutrient sources to optimize soil fertility and crop productivity ^[28]. The goal of integrated nutrient management (INM), a comprehensive, system-based strategy, is to maintain crop output and soil fertility by maximizing the combined use of organic, inorganic, and biological nutrient sources as opposed to maximizing the use of single-input fertilizers ^[29]. INM's major goal is to provide nutrients at times and quantities that satisfy crop demand while preserving soil health, long-term economic viability, and environmental quality ^[30]. INM increases nutrient cycling, improves soil structure and organic matter, and lessens reliance on chemical fertilizers and related pollution risks by purposefully combining mineral fertilisers with organic amendments like farmyard manure, composts, crop residues, and green manures, as well as biological inputs like nitrogen-fixing crops and biofertilizers ^[31]. The synchronisation of nutrient release with crop absorption through soil testing, balanced

fertilisation, staged treatments, and the use of slow or controlled-release sources in accordance with 4R nutrient management is a fundamental tenet of INM [32]. This system-level optimisation increases yield stability, decreases losses from leaching, runoff, and volatilisation, and improves nutrient usage efficiency. Agronomically, INM boosts productivity, enhances crop quality and water-use efficiency, and creates resilient soils that can support long-term agricultural intensification.

Ecologically, it reduces greenhouse gas emissions, mitigates eutrophication, and promotes biodiversity and carbon sequestration [33].

Integrated nutrient management has been shown to improve yield and economic returns in vegetables; for example, combining organic and inorganic sources, supports sustainable cultivation. Foliar sprays of 0.5% zinc sulphate and other micronutrients during April-May or September-October enhance plant health and may be soil-applied for improved uptake [34]. chilli experiments at SHUATS (2021-22) indicated that combining 100% NPK with 10 t ha⁻¹ vermicompost gave the highest yield, quality, and benefit-cost ratio [35], significantly improved cucumber (cv. Sheetal) growth, yield (6.0 kg/vine), fruit quality (TSS 4.8 Brix; ascorbic acid 8.8 mg/100 g), and soil fertility compared to full chemical fertilization [36]. And partial substitution of chemical fertilizers with organic and biofertilizers enhanced soil fertility, with 75% RDF plus vermicompost, Azotobacter, and PSB giving the highest seed yield in niger [37].

1.6 Relevance of integrated nutrient management in horticultural and agronomic systems

Vegetable and horticultural crops form the backbone of nutritional security and income generation in smallholder and commercial farming systems. Integrated Nutrient Management (INM) is especially important in horticultural and agronomic systems because it successfully addresses high crop nutrient demands while also maintaining soil health, productivity, and output quality. Vegetables, fruits, flowers, and high-value cash crops are examples of horticultural crops that have stringent quality criteria pertaining to size, colour, flavour, storability, and nutritional density [38]. When compared to relying solely on mineral fertilizers, research consistently demonstrates that INM improves yields, quality characteristics, and tissue nutrient content in horticultural crops. It also improves grain protein and biochemical quality in main field crops [39]. INM has proven to be widely applicable to a variety of production methods and short- and long-duration crops. In addition to improving soil quality and system production in long-duration systems including orchards, sugarcane, cotton, and intense cropping cycles, it works well in short-season vegetables, cereals, and pulses [40]. Crucially, via specific combinations of organic, inorganic, and biological inputs, INM principles may be used to protected cultivation, soilless and controlled-environment systems, open-field agriculture, and stress-prone settings including dry and salt areas.

INM's resilience as a system-based nutrient approach is demonstrated by its scalability throughout agro-ecological zones, from wet tropics to semi-arid, coastal, and desert areas [41]. INM improves yield stability, resilience, and fertilizer usage efficiency across farming systems when locally tailored to soil type, climate, and crop requirements. All things considered, INM offers a scalable and adaptable framework to concurrently address the sustainability issues of agronomic systems under various environmental circumstances and the high nutrient requirements of horticultural crops.

1.7 Need for a mechanistic and innovation-oriented synthesis

The literature on Integrated Nutrient Management (INM) is still dispersed among crops, geographical areas, and management techniques despite a great deal of research on the subject. It is frequently dominated by short-term, site-specific studies that restrict generalization and mechanistic knowledge [42]. While providing little information on the underlying soil plant microbe interactions that control nutrient cycle and efficiency, the majority of reviews have an emphasis on yield responses and wide-ranging environmental benefits. Despite being underrepresented in INM syntheses, rhizosphere processes such as root exudation, microbial consortia, and localised nitrogen and phosphorus transformations are crucial to nutrient availability and stress resilience. Simultaneously, new digital and precision technologies such as sensors, modeling, machine learning, nano-fertilizers, and controlled-environment systems are being used more often in nutrient management, but they are still not well integrated with traditional INM frameworks [43]. To promote scalable, climate-resilient nutrition solutions, these gaps underscore the necessity of a global, cross-system synthesis that connects INM practices with mechanistic knowledge, rhizosphere biology, and technology innovation [44].

1.8 Objectives, scope, and novelty of the present review

The purpose of this review is to provide a mechanistic, innovation-oriented synthesis of Integrated Nutrient Management for horticultural and vegetable cropping systems by delving into soil-plant-microbe and rhizosphere interactions that affect nutrient-use efficiency, yield stability, and system resilience [45]. In order to improve sustainability results, it also looks at new developments such as bio stimulants, nano-inputs, precision nutrient technologies, and soilless or controlled-environment systems and assesses how well they integrate into INM frameworks [46]. The scope includes open-field and protected cultivation, staple and cash-crop systems, horticultural and field crops, and various agro-ecological zones around the globe. This study places rhizosphere processes at the centre of research and methodically incorporates technology advancements to create a cross-scale framework, in contrast to previous INM evaluations that mainly concentrate on practices and yield outcomes. By doing this, it aims to increase scientific knowledge while influencing the creation of policies, climate-smart nutrition plans, and suggestions for sustainable intensification that are particular to a given region.

2. Conceptual framework and principles of integrated nutrient management (INM)

2.1 Definition, scope, components of INM

Integrated fertilizer Management (INM) is widely acknowledged as a holistic, systems-based strategy that maximizes the utilization of all available fertilizer sources and routes in order to maintain crop yield, soil health, and environmental quality [46]. INM is technically described across the literature as the prudent and balanced integration of biological, inorganic, and organic nutrient sources to satisfy crop nutrient needs while preserving soil fertility and reducing negative environmental effects [47].

Optimizing nutrient inputs rather than maximizing them is a key tenet of INM, which aims to improve resource sustainability, economic returns, and nutrient usage efficiency by matching crop demand with nutrient availability over time and location. The majority of definitions specifically highlight the long-term preservation of the physical, chemical, and biological characteristics of soil as well as the mitigation of pollution, greenhouse gas emissions, and nutrient losses [48]. Cereals,

pulses, cash crops, and horticultural crops from various agro-ecological areas are all included in the purview of INM, which

spans from the field scale to complete cropping systems and the wider soil plant microbe environment continuum ^[49].

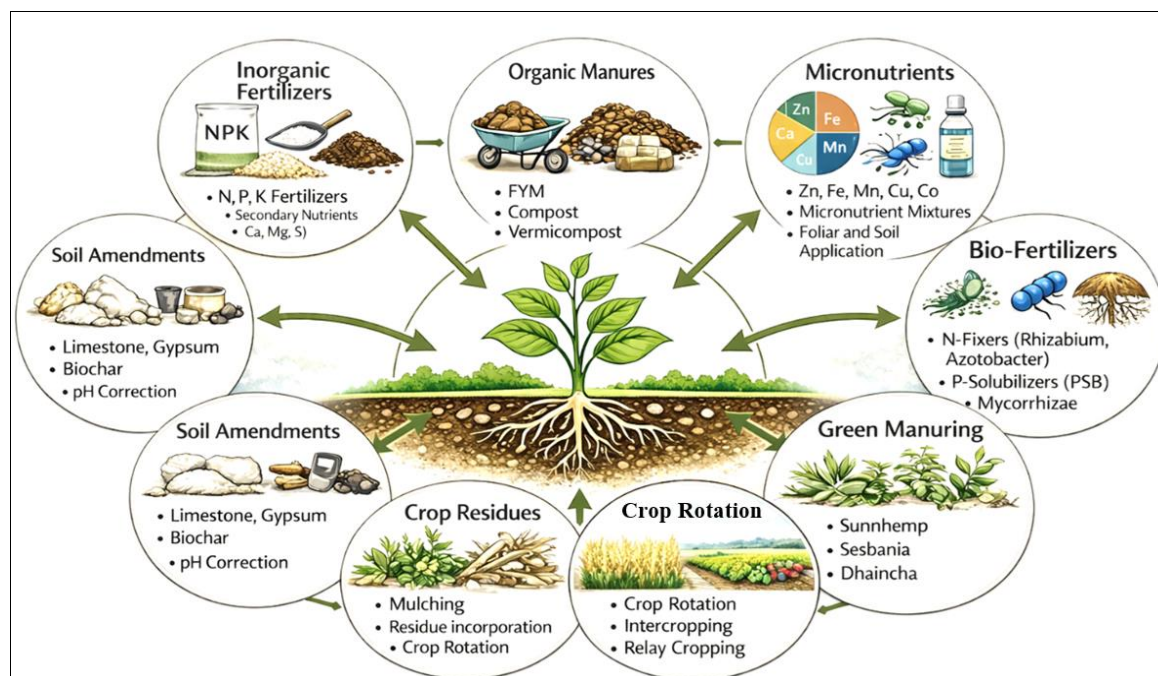


Fig 1: Components integrated fertilizer management (INM)

2.2 Core components of integrated nutrient management

Integrated Nutrient Management (INM) is based on the judicious integration of multiple nutrient sources and complementary management practices to sustain crop productivity, enhance soil health, and minimize environmental degradation. Each component contributes uniquely to nutrient supply, cycling, synchronization with crop demand, and reduction of losses within the soil-plant-atmosphere continuum.

2.2.1 Inorganic fertilizers

Inorganic fertilizers are an important part of Integrated Nutrient Management (INM) because they may provide accurately defined and quickly accessible macro- (N, P, K), secondary- (S, Ca, Mg), and micronutrients to fulfill immediate and peak crop

nutrient demands. While uncontrolled usage can result in soil acidity, salinity, nutrient imbalance, and environmental damage, balanced application improves crop production and quality. Mineral fertilizers are consequently administered in appropriate forms and balanced dosages within INM frameworks according to crop need and soil testing ^[50]. While lowering losses from leaching, volatilization, and nitrous oxide emissions, precision techniques including split application, band placement, and synchronization with crop growth phases greatly increase fertilizer usage efficiency. Although there hasn't been much large-scale field validation, recent developments including coated formulations, slow- and controlled-release fertilizers, and newly developed nano-fertilizers are intended to further match nutrient delivery with plant absorption.

Table 1: Yield effects of inorganic fertilizers in horticultural and vegetable crops.

Crop / system	Inorganic fertilizer treatment (no organics)	Main yield / growth response vs. control	Reference
Broccoli (greenhouse)	NPK at 0, 300, 500, 700 kg ha ⁻¹ , 3 splits	700 kg ha ⁻¹ NPK gave highest main head yield and several growth traits; all NPK doses > unfertilized control for growth, yield and quality traits	[51]
Carrot (field, India)	60:50:60 kg N:P:K ha ⁻¹ (inorganic)	Among inorganic treatments, 60:50:60 NPK produced highest total root yield (388.82 q ha ⁻¹) and best economics vs. other chemical doses and unfertilized plots	[52]
Tomato (pot/field type)	NPK fertilizers (polyvinyl alcohol-urea-K ₃ PO ₄) at different N levels (NPK35, 50, 65)	All NPK treatments increased vegetative growth, yield and chemical content vs. no fertilizer; NPK50 (31.7% N) gave maximum yield and quality	[53]
Global food crops (incl. many vegetables)	Mineral fertilizers (various NPK, single nutrients) vs. no fertilizer	Across 551 field experiments, fertilizer increased average yield by 30.9% and improved overall nutritional quality by 11.9%, with vegetables the most responsive group	[54]
Newly reclaimed vegetable soils (China)	Chemical fertilizer (NPK, CF treatment) vs. no fertilizer	Soil Olsen-P increased by 210.6% under mineral fertilization, supporting higher P availability for vegetable production compared with unfertilized soil	[55]
Greenhouse vegetables (China)	Long-term inorganic fertilizer plots vs. no fertilizer	Inorganic fertilization increased abundance and diversity of soil antibiotic resistance genes, indicating strong fertilizer-driven changes in soil microbial environment	[56]

2.2.2 Organic manures

Organic fertilizers are essential for sustainable agriculture

because they enhance soil quality, increase crop yields, and improve environmental results. In environmentally friendly

agricultural methods, organic fertilizers fulfill the following purposes ^[57]. Compost, vermicompost, farmyard manure (FYM), and other organic wastes are examples of organic manures that are essential to integrated nutrient management because they increase soil organic carbon, improve soil structure and aggregation, increase water-holding capacity, and provide both macro and micronutrients ^[58]. When organic manures and mineral fertilizers are combined over an extended period of

time, stable organic nitrogen pools are built up, which improves yield over time and increases the availability of micronutrients like Zn, Fe, Mn, and Cu ^[59]. Although alternate sources, such as municipal composts and dumpsites, have demonstrated great potential to enhance crop growth and nutrient absorption, their use necessitates thorough quality monitoring because of the possibility of heavy metal buildup, underscoring the necessity for controlled use within INM frameworks.

Table 2: Yield effects of organic fertilizers in horticultural and vegetable crops

Crop/system	Organic fertilizer treatment (no chemical NPK)	Yield/response vs. unfertilized control	Reference
Mixed vegetables (7-crop rotation: eggplant, tomato, cauliflower, onion, muskmelon, fennel, endive)	Biowaste compost 30-15 Mg ha ⁻¹ yr ⁻¹ (Com, no mineral NPK)	Compost maintained SOC at 1.2–1.4% and gave yields always ≥ mineral fertiliser and much higher than control, across 7 years 1	[60]
Greenhouse vegetables (China, multiple species)	Organic fertilizer alone vs. no organic	Organic fertilizer increased vegetable yield 44.1% on average vs. no organic input; leafy vegetables up to +76.4% 8	[61]
Tomato (global meta-analysis vs. no fertilizer)	Animal, plant, mixed organic manures & composts	Organic fertilizer increased tomato yield by 42.2% on average; also raised soluble sugar (+42.2%), lycopene (+24.0%) and vitamin C (+19.0%) 16	[62]
Tomato (global meta-analysis vs. 100% chemical)	Various organic fertilizers alone	Organic fertilizers gave +3.5% yield and large increases in SOM (+24%), total N (+33%), P (+24%), K (+45%) vs. 100% chemical fertilizer 4	[63]
Swiss chard (field, Italy)	Vermicompost from cattle manure (alone or with biochar)	Vermicompost alone significantly increased plant height, leaf area and yield; yields comparable to ammonium nitrate and far above unfertilized soil or biochar alone 11	[64]
Greenhouse lettuce (degraded soil)	Poultry manure, vinasse-based fertilizer, insect frass (90 kg N ha ⁻¹)	All organic fertilizers increased shoot fresh weight; best treatments +75% yield vs. control, with lower leaf nitrate and Pb and higher soil enzyme activity	[65]

2.2.3 Micronutrients

Micronutrients including zinc (Zn), iron (Fe), boron (B), manganese (Mn), molybdenum (Mo), and copper (Cu) are necessary for photosynthesis, enzymatic activity, reproductive development, and grain quality, although they are needed in trace amounts. In intensively farmed systems, deficiencies of these elements are becoming more common, especially in high-pH, calcareous, and continually fertilized soils, where they

severely limit crop yield and nutritional quality. By enhancing DTPA-extractable micronutrient pools and plant uptake through chelation, enhanced microbial activity, and localized pH modification, the combination of mineral micronutrient fertilisers with organic and green manures within INM frameworks improves micronutrient efficiency and maintains long-term soil fertility ^[66].

Table 3: Yield effects of micronutrients in horticultural and vegetable crops

Crop (example)	Micronutrient strategy	Approx. yield gain vs. control	Reference
Potato	Fe + Ca + B + Zn foliar mix	51% higher tuber yield	[67]
Watermelon	Zn + B foliar + K	32% higher fruit yield	[68]
Onion	B 0.25% + Zn 0.5% foliar	31% higher bulb yield	[69]
Cauliflower	B + Mo + Zn with RDF	Max. curd yield, faster maturity	[70]

2.2.4 Biofertilizers

Biofertilizers, such as Rhizobium, Azotobacter, phosphate-solubilizing bacteria (PSB), plant growth-promoting rhizobacteria (PGPR) consortia, and mycorrhizal fungi, play important roles in nutrient acquisition and plant growth promotion. These microbes aid in the biological fixation of nitrogen, the solubilization and mineralization of phosphorus

and other nutrients, and the synthesis of siderophores and phytohormones that promote root growth and improve iron uptake ^[71]. These processes allow biofertilizer inoculants to support sustainable crop production while lowering reliance on synthetic inputs, enhance nutrient usage efficiency, and partially replace chemical nitrogen and phosphorus fertilizers ^[72].

Table 4: Yield effects of biofertilizers in horticultural and vegetable crops

Crop / Plant	Biofertilizer Type	Key Effects on Growth, Flowering, Fruiting, and Yield	Notes	Source
Horned melon	Trichoderma-based	Increased number of male and female flowers; more fruits per plant; delayed flowering time	Higher doses (0.3-0.4 g/pot) produced more flowers	[73]
Guava “Crystal”	Biofertilizer + pruning/bending	Increased shoots (+5%), shoot length (+9%), leaves (+10%), flower number (+89%), fruit number (+78%)	No significant effect on fruit quality traits	[74]
Strawberry	Various biofertilizers and bio capsules	Improved vegetative growth, flowering duration, flower and fruit number, and yield	Effective under organic farming systems	[75]

Brinjal (Eggplant)	Trichoderma + <i>Pseudomonas fluorescens</i>	Highest flowers per cluster (4.67), fruits per plant (16.99), fruit length (16.86 cm), yield (2.23 kg/plant)	Best results when combined with inorganic fertilizers	[76]
Cauliflower	<i>Bacillus megaterium</i> + <i>Glomus mosseae</i> + others + vermicompost + phosphate fertilizer	Increased flower disc weight, total yield, nitrogen and phosphorus content	Integrated biofertilizer + organic + mineral fertilizers were optimal	[77]
African marigold	Azotobacter + Azospirillum + Mycorrhizae	Increased plant height (107 cm), branches, leaves, flower number (42/plant), flower yield (~459 g/plant)	All growth and yield parameters improved significantly	[78]
Gladiolus	Azospirillum, Azotobacter, Rhizobium	Increased plant height, spike length, florets per spike, improved nutrient uptake	Azospirillum treatment showed highest values	[79]
Tomato	Microalga <i>Acutodesmus dimorphus</i> extracts	Faster germination (2 days earlier), increased plant height, more flowers and branches per plant	Foliar spray and soil application both effective	[80]

2.2.5 Green manuring

Green manuring, which includes both leguminous and non-leguminous crops, is a successful INM method for increasing soil fertility by adding biologically fixed nitrogen and organic matter. By increasing Ca²⁺ availability and lowering exchangeable sodium percentage (ESP) and hazardous ion concentrations, the addition of green manures enhances soil

aggregation, porosity, and biological activity while also aiding in the restoration of salty and alkali soils [81]. In intensive cropping systems, green manure crops greatly reduce nutrient leaching losses and improve fertilizer availability to future crops by increasing the mobilization and recycling of nitrogen, phosphorous, potassium, and numerous micronutrients [66].

Table 5: Yield effects of green manuring in vegetables, fruits and flowers

Crop group	Main crop	Green manure species / practice	Yield effect vs. no green manure (control)	Reference
Vegetable (leafy)	Romaine lettuce	Turnip or swede grown as green manure in rotation (high tunnel, organic)	Lettuce yield +63.3% after turnip/swede green manure vs. no green manure	[82]
Vegetable (grain/legume)	Broad bean (early)	Turnip or swede green manure in rotation	Grain yield +90.9% (turnip) and +59.1% (rutabaga) vs. control	
Vegetable (fruit vegetable)	Hot pepper	Turnip or swede green manure in rotation	Fruit yield +102% after turnip and +189% after rutabaga vs. control	
Vegetable (leafy)	Leek	Phacelia used as green manure in rotation	Whole-plant yield +15.8% vs. control	
Vegetable (leafy herb)	Leaf parsley	Phacelia and buckwheat as green manures in rotation	Total leaf yield +197% on average vs. no green manure	
Vegetable (leafy)	Lettuce (cv. Veradarz, Manushak)	Bean, green pea, soybean as green manure before lettuce	Lettuce yields +8.1–30.0%; maximum 358.4 c/ha with soybean green manure	[83]
Vegetable (leafy)	Chinese cabbage, asparagus lettuce, Shanghai green, oilseed lettuce	Green manure component in organic fertilizer mixtures	Green manure alone had highest chlorophyll; yields generally similar to manure-only control (no strong yield change reported)	[84]
Vegetable (flower/curd)	Broccoli	Common vetch pre-crop incorporated as green manure (Ve)	Vetch alone gave lowest curd yield (819.7 g plant ⁻¹), below chemical and vermicompost treatments	[85]
Vegetable (fruit vegetable)	Cucumber (organic system)	Green manure only vs. no fertilizer	Fruit yield 7853.7 kg ha ⁻¹ with green manure vs. 4118.0 kg ha ⁻¹ in control (≈ +90%)	[86]
Fruit (orchard citrus)	Assam lemon	Tephrosia spp. green manuring with 50% RDF vs. RDF alone	Highest fruit yield 21.35 t ha ⁻¹ , more fruits plant ⁻¹ and heavier fruits than RDF; green manure alone lower	[87]
Fruit (orchard pear)	Pear	Intercropped leguminous green manures (vetch spp.) in alleys	Legume green manures increased fruit yield; hairy vetch gave highest yield and +14.4% soluble solids vs. control	[88]
Fruit (orchard banana)	Banana cv. Grand Nain	Dhaincha (Sesbania) single, double, triple green manuring	Fruit yield 108.99 t ha ⁻¹ with triple green manuring vs. 83.02 t ha ⁻¹ in control (≈ +31%)	[89]
Fruit (strawberry)	Strawberry	Soybean + cowpea green manure (with or without poultry slurry)	Green manure + poultry slurry increased fruit yield and soil organic matter vs. control; exact % range 1st yr 10.68–22.33 t ha ⁻¹ , 3rd yr 10.68–16.98 t ha ⁻¹	[90]
Vegetable (fruit vegetable)	Eggplant	Bean, pea, soybean as green manures	Eggplant yield vs. no green manure: +24.3% (soybean), +18.2% (bean), +14.5% (pea)	[91]

2.2.6 Crop residues

A crucial part of integrated nutrient management is crop residue management by absorption or surface mulching, which promotes soil microbial activity, improves soil organic carbon stocks, and makes nutrient recycling easier. Retained residues help to improve soil structure, control soil temperature and moisture, and lessen soil erosion. In cropping systems that are diverse and focused on conservation, the gradual breakdown of crop residues

releases nitrogen, phosphorous, potassium, and other vital micronutrients, boosting nutrient availability for subsequent crops and increasing total fertilizer usage efficiency. Crop residue return in vegetables and mixed fruit–vegetable greenhouse systems generally increases yield by about 5–12%, with larger gains (up to ~19%) when residues are well incorporated, rotations are used, and conditions favor soil organic matter build-up [92–94].

2.2.7 Soil amendments

Soil supplements such as lime, gypsum, charcoal, and sulfur are important in Integrated Nutrient Management because they adjust soil pH, reduce salinity and sodicity, and modify cation exchange capacity (CEC) ^[95], all of which affect nutrient availability and soil structural stability. While sulfur treatment can improve nutrient availability in alkaline soils, lime and gypsum are commonly employed to improve acidic and sodic soils, respectively. While biochar has demonstrated potential to boost CEC, nutrient retention, and carbon stability, field-scale data across agro-ecologies is still few. In contrast, the combined application of sulfur and organic additions promotes soil aggregation under saline circumstances. Organic soil amendments such as compost, manure, biochar, vermicompost, and biofertilizers consistently improve soil quality and horticultural crop productivity, with reported yield increases of 25–100%. In vegetables, compost and organic fertilizers enhanced bean, zucchini, and pepper yields and improved soil pH, organic matter, and nutrient availability ^[96]. Humic substances combined with biochar or rock dust increased zucchini yield by 52–107% in alkaline soils ^[97] while lime, phosphorus, and *Trichoderma* improved tomato yield and shelf life in acidic soils ^[98]. Biochar, vermicompost, and fulvic acid increased greenhouse tomato yield by more than 30% by improving soil structure and nutrient status ^[99]. Organic fertilizers with straw mulch enhanced squash yield and fruit nutrient content ^[100], and long-term biowaste compost application sustained vegetable yield and soil organic carbon ^[101].

In fruit crops, composts, manures, green manures, and biofertilizers improved soil fertility, microbial diversity, water retention, and fruit yield and quality ^[102]. In ornamental crops, garden compost increased flower yield up to fivefold, whereas bark and peat composts showed limited benefits. Poultry litter improved soil biological activity but caused phosphorus accumulation, indicating the need for balanced nutrient management ^[103]. Meta-analyses report an average yield increase of about 27% with organic amendments over mineral fertilizers, mainly due to higher soil organic carbon, nitrogen availability, and microbial activity ^[104]. However, responses vary with soil

type, pH, amendment type, and dose, and inappropriate use may cause nutrient imbalances ^[104]. Overall, properly selected and managed organic amendments reliably enhance soil health and crop yield in vegetable, fruit, and ornamental systems.

2.2.8 Leguminous crops

Through biological nitrogen fixation facilitated by *Rhizobium* symbiosis, leguminous crops significantly contribute to Integrated Nutrient Management, making up a significant portion of biologically fixed nitrogen globally. Legumes improve soil nitrogen status, soil organic matter, and micronutrient dynamics when added to crop rotations or utilised as green manures. They also help restore salty soils by improving soil structure and ionic equilibrium. While leguminous crops, residue retention, effective irrigation management, and diversified cropping systems enhance biological nitrogen inputs, nutrient recycling, and system-level nutrient balance, soil amendments (lime, gypsum, and phosphate materials) correct pH, salinity, and toxicity constraints ^[105].

2.2.9 Irrigation water management

Nutrient availability and absorption are strongly impacted by irrigation timing and water quality, especially salinity, which have a significant impact on nutrient transport, leaching losses, and soil redox dynamics. By coordinating water and nutrient supply with crop demand, the integration of fertigation with carefully controlled irrigation improves nutrient use efficiency. However, in intensive production systems, careful management of salinity buildup and leaching fractions is crucial to preventing soil structural degradation and long-term fertility decline.

2.2.10 Cropping systems

Crop rotation, intercropping, and precision-based cropping are all important aspects of cropping system design that control nutrient demand, recycling, and system-level nutrient balance. In order to maintain soil fertility and long-term production under Integrated Nutrient Management frameworks, diversified systems interfere with pest and disease cycles, increase resource efficiency, and operate in concert with organic manures, green manures, and biofertilizers.

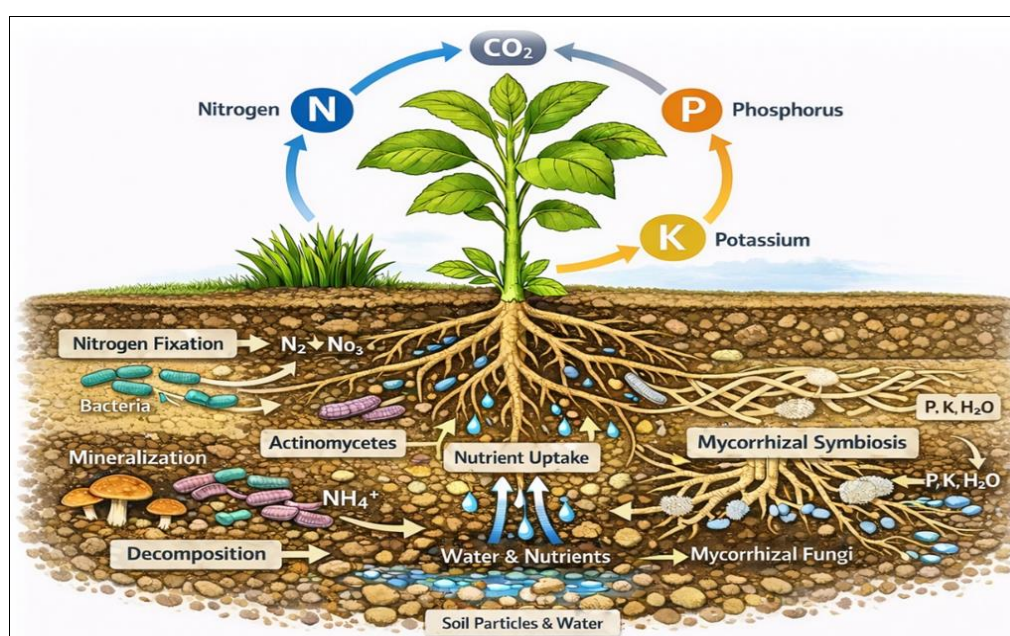


Fig 2: Soil-Plant microbe interactions and nutrient cycling in the rhizosphere.

2.3 Nutrient pathways in integrated nutrient management

INM modulates nutrient routes throughout the soil-plant-microbe continuum in order to maximize availability and reduce losses. Mineral fertilisers, organic additions, biological nitrogen fixation, irrigation water, and atmospheric deposition are some of the ways that nutrients enter the system ^[106]. Through mineralisation-immobilisation, sorption-desorption, and redox-mediated processes that buffer nutrient supply over time, nutrients are transformed and stored in organic matter pools, exchange sites, and microbial biomass within the soil. Plant absorption is coordinated with crop need by matching nutrient availability, rate, timing, and positioning, especially during crucial growth phases. Through balanced fertilization, residue retention, enhanced soil structure, and coordinated water-nutrient management, INM simultaneously seeks to decrease loss paths, such as leaching, runoff, erosion, volatilization, and denitrification. INM operates as a system-based approach that improves nutrient-use efficiency, stabilizes yields, and protects soil and environmental quality across a variety of agro-ecological systems through this integrated management of components and pathways.

3. Soil-plant-microbe interactions in INM: focus on rhizosphere processes

Understanding the interactions between roots, microorganisms, and soil chemistry in the rhizosphere is becoming more and more important for Integrated Nutrient Management (INM) in order to mobilize nutrients effectively and sustainably. Microbially driven solubilization, pH adjustment, and root exudation are important levers to lower the requirement for synthetic fertilizer while preserving yields.

Schematic illustration showing the relationships among plant roots, soil microorganisms, and nutrient cycles (N, P, K, and C), including nitrogen fixation, mineralization, decomposition, and mycorrhizal symbiosis influencing plant growth and soil health.

3.1.1 Root exudates' function in nutrient dynamics

N, P, Fe, Zn, and Mn are mobilized by root exudates (sugars, amino acids, organic acids, phenolics, enzymes, and proteins), which also serve as signals to symbionts (rhizobia, mycorrhizae, and PGPR) ^[107]. Extracellular enzymes and secreted proteins release organic N and P, whereas organic acids and phytosiderophores chelate Fe, Zn, and solubilize Ca/Fe/Al phosphates. Additionally, exudates select P-solubilisers, N-fixers, and disease-suppressive communities, so structuring the rhizosphere microbiome ^[108].

3.1.2 Rhizosphere pH modification and nutrient availability

Proton/HCO₃⁻ release, food intake balance, and organic acid exudation are how roots change pH. In neutral-alkaline soils, acidification often increases the solubility of Fe, Zn, Mn, and sparingly soluble P; a pH decrease of only one unit can increase the solubility of Zn by around 100 times, While P gets locked at extremely low or high pH, optimal macronutrient availability (N, K, Ca, Mg, and S) frequently occurs about pH 6-7. Nutrient efficiency is influenced by genotypic variations in acid exudation and proton pumping ^[109].

3.1.3 The rhizosphere's solubilization and mobilization of nutrients

Through increased microbial activity, enzyme synthesis, and exudate-driven weathering, rhizosphere activities make most nutrients more available than in bulk soil. Despite increased phosphatase activity ^[110], meta-analysis reveals that there is

typically +10% available N but -12% available P because of strong plant-microbe competition. The mobilization of organically bound N, P, and S is closely related to rhizosphere priming, which is the activation of soil organic C breakdown. Through N fixation, P/K/Zn solubilization, and siderophore-mediated Fe acquisition, PGPR and other PBRM improve nutrient utilization efficiency by around 20-40%.

3.1.4 Integration in frameworks for INM

Specific PGPR/PBRM inoculants for N fixation and P/micronutrient solubilization, organic amendments to boost rhizosphere microorganisms, and nutrient-efficient genotypes with robust exudation and pH control are all things that INM may intentionally combine. Aiming for pH ranges that balance the availability of macro- and micronutrients (≈6-7), management should take advantage of localized rhizosphere acidification or alkalization for certain elements. Nano-fertilizers and advanced pH and exudation monitoring are two new methods to optimize rhizosphere processes for greater nutrient efficiency ^[108].

3.2 Microbial mediation of nutrient cycling

The cycling of carbon, nitrogen, phosphorus, and sulfur is fueled by soil microbes, which regulates nutrient availability and soil fertility over the long run. Microbial activities include decomposition, nitrogen fixation, mineralization, nitrification, denitrification, and phosphorus solubilization control how nutrients are converted into forms that plants may use in Integrated Nutrient Management systems ^[110]. These biogeochemical cycles are intimately related, and microbial activity and functional efficiency are significantly influenced by soil carbon and phosphorus. Microbial diversity and nutrient turnover are encouraged by methods that maintain balanced nutrition and increase organic carbon supplies. INM increases nutrient usage efficiency and fortifies the sustainability of horticultural and vegetable production systems by promoting beneficial microbial communities through organic amendments, ideal pH control, and targeted inoculation.

3.3 Mycorrhizal associations and nutrient acquisition

Mycorrhizal fungi work in symbiotic relationships with plant roots and are essential for enhancing the intake of nutrients that are not easily moved, particularly micronutrients and phosphorus. They increase the effective root surface area and provide plants access to nutrient pools outside of the root depletion zone by means of vast hyphal networks. Arbuscular mycorrhizal fungi play a major role in the uptake of nitrogen and phosphorus by plants and are particularly significant for horticultural and vegetable crops in Integrated Nutrient Management systems. By direct absorption and solubilization, mycorrhizae also improve the intake of potassium, sulfur, zinc, copper, and iron ^[111]. Furthermore, they enhance carbon sequestration, soil structure, and nutrient cycling through their interactions with advantageous soil bacteria. Mycorrhizal relationships are an essential biological element of sustainable nutrient management in horticultural production systems because they improve nutrient usage efficiency and stress tolerance.

3.4 Enzyme activity and nutrient turnover

Soil enzymes are key regulators of nutrient turnover and serve as sensitive indicators of soil biological health in Integrated Nutrient Management systems. Enzymes such as urease, protease, phosphatase, β-glucosidase, cellulase, arylsulfatase,

and dehydrogenase drive the cycling of nitrogen, phosphorus, carbon, and sulfur by decomposing organic matter and releasing plant-available nutrients ^[111]. Integrated application of organic and mineral fertilizers enhances microbial activity and enzyme production, leading to faster nutrient mineralization and improved nutrient availability. Increased enzyme activity supports synchronized nutrient release with crop demand, improves nutrient use efficiency, and reduces losses. Moreover, enzyme activities are strongly linked with soil organic carbon, nutrient status, and crop yield, making them reliable indicators of soil fertility and sustainability in horticultural and vegetable production systems.

4. Integrated nutrient management's mechanisms and use in crop production

Integrated Nutrient Management (INM) improves crop productivity and sustainability by optimizing nutrient availability, enhancing soil biological activity, and improving nutrient use efficiency. A balanced nutrient supply and a beneficial soil, plant, and microbial environment are ensured by the simultaneous application of organic, inorganic, and biological nutrient sources. Below is a discussion of the main ways that INM affects agricultural yield.

4.1 Nutrient availability and synchronization with crop demand

Integrated Nutrient Management (INM) improves nutrient availability by synchronizing nutrient release with crop demand through the combined use of mineral fertilizers and organic sources. Mineral fertilizers provide immediately available nutrients that support early crop establishment and rapid vegetative growth, whereas organic manures, green manures, and crop residues decompose gradually, releasing nutrients steadily during later growth stages such as tillering, flowering, and grain filling ^[112]. This complementary release pattern ensures a continuous and balanced nutrient supply, enhances nutrient use efficiency, and reduces losses through leaching, volatilization, and denitrification compared with sole mineral fertilization ^[113]. Furthermore, the incorporation of organic amendments increases soil organic matter, cation exchange capacity, and buffering capacity, thereby stabilizing nutrient availability under fluctuating soil moisture and temperature conditions and promoting long-term soil fertility and sustained crop productivity.

4.2 Improvement in nutrient use efficiency

Nutrient Use Efficiency (NUE) is a key determinant of sustainable crop production, and Integrated Nutrient Management (INM) enhances NUE by improving nutrient retention, uptake, and biological cycling in the soil-plant system. Long-term studies indicate that partial substitution of mineral nitrogen with organic sources such as farmyard manure, green manure, and crop residues can significantly increase NUE while maintaining or even improving yields ^[114]. The addition of organic matter improves soil organic carbon, cation exchange capacity, water-holding capacity, porosity, and reduces bulk density, thereby retaining nutrients within the root zone and enhancing fertilizer recovery efficiency. Furthermore, INM stimulates microbial biomass and enzyme activity, promoting biological nitrogen fixation, phosphorus solubilization, and micronutrient mobilization, especially when combined with biofertilizers such as *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria. Improved soil structure under INM also supports better root growth and exploration of soil volume,

resulting in greater nutrient uptake and a higher proportion of applied nutrients being effectively utilized by crops ^[115]. Overall, INM increases NUE by reducing losses, enhancing nutrient recovery, and lowering dependence on synthetic fertilizers while sustaining crop productivity.

4.3 Enhancement of soil microbial activity and rhizosphere processes

Integrated Nutrient Management (INM) enhances soil microbial activity and rhizosphere processes by supplying carbon-rich organic amendments that stimulate microbial biomass and diversity. Long-term application of farmyard manure combined with mineral fertilizers significantly increases microbial biomass carbon and nitrogen, as well as bacterial and fungal populations, compared with sole inorganic fertilization ^[116, 117]. Partial substitution of mineral fertilizers with organic sources improves rhizosphere microbial diversity and beneficial microbial groups, leading to a more biologically active soil environment. The inclusion of biofertilizers such as *Azotobacter*, phosphate-solubilizing bacteria (PSB), potassium mobilizers, and other plant growth-promoting rhizobacteria further enhances microbial populations in the root zone and strengthens root-microbe interactions.

INM also markedly increases key soil enzymatic activities including dehydrogenase, phosphatase, urease, β -glucosidase, and fluorescein diacetate (FDA) hydrolysis indicating enhanced microbial respiration and improved carbon, nitrogen, and phosphorus cycling. These enhanced biological and enzymatic processes accelerate nutrient mineralization and turnover, making the rhizosphere a highly active zone for nutrient transformation and exchange under INM systems, thereby improving nutrient availability and plant growth.

4.4 Root growth and plant physiological processes

Integrated Nutrient Management (INM) improves root growth and plant physiological performance by enhancing soil physical conditions and ensuring balanced nutrient supply. The addition of organic amendments lowers bulk density while increasing porosity and water-holding capacity, creating favorable conditions for root elongation and proliferation. Long-term INM in maize, wheat, and vegetable systems significantly increases root length, surface area, and root-mass density compared with sole mineral fertilization while crops such as brinjal and pomelo develop larger root systems with more fine roots and root tips, directly enhancing nutrient uptake. Balanced, multi-source nutrition under INM also improves photosynthetic rate, chlorophyll content, and metabolic enzyme activities, leading to higher biomass accumulation and yield across cereals and horticultural crops ^[118]. These stronger rootshoot systems contribute to improved tolerance to drought and nutrient stress.

4.5 Integrated nutrient synergy, environmental stability, and soil-plant microbe functioning

Integrated Nutrient Management (INM) enhances nutrient interactions, environmental stability, and soil-plant microbe functioning through the combined use of organic, inorganic, and biological nutrient sources. By improving the synchrony and balance of N, P, K, and micronutrients, INM promotes synergistic nutrient interactions such as N-P and N-K combinations which increase fertilizer efficiency and crop yield when applied in balanced proportions. The addition of organic matter raises cation exchange capacity and promotes micronutrient chelation, thereby enhancing nutrient availability and reducing antagonistic interactions ^[118].

INM also strengthens environmental stability by increasing soil organic matter and aggregation, which reduce runoff, erosion, and nutrient leaching losses. The integration of split nitrogen applications with organic amendments improves synchronization between nutrient release and crop demand, lowering surplus nitrogen and minimizing ammonia volatilization, denitrification, and greenhouse gas emissions while sustaining yields. Furthermore, INM fosters integrated soil-plant microbe functioning by increasing soil organic carbon and microbial biomass, which enhance nutrient mineralization and availability. Improved root systems under INM release diverse root exudates that stimulate beneficial microbial communities and strengthen rhizosphere processes^[119]. This positive feedback among soil properties, root development, and microbial activity underpins long-term soil fertility, resilience to climatic stress, and sustained agricultural productivity.

5. Comprehensive impact of integrated nutrient management on soil health and long-term sustainability

Integrated Nutrient Management (INM) substantially improves soil health by simultaneously enhancing its physical, chemical, and biological properties, strengthening soil organic carbon (SOC) stocks, and supporting long-term ecosystem sustainability. Long-term studies show that combining farmyard manure, crop residues, compost, biofertilizers, and mineral fertilizers reduces bulk density while increasing porosity and water-holding capacity, thereby improving aeration, infiltration, and root growth compared with sole chemical fertilization^[120]. Chemically, INM increases SOC, available N, P, K, and micronutrients such as Zn, Fe, Cu, and Mn, enhances cation exchange capacity, and stabilizes soil pH, leading to improved nutrient retention and balanced fertility. Biologically, INM stimulates microbial biomass carbon and nitrogen, respiration, and key enzymatic activities including dehydrogenase, phosphatase, urease, and FDA hydrolysis while promoting richer microbial diversity and greater soil fauna activity compared with mineral fertilizers alone. Regular addition of organic materials increases both active and stable carbon pools, contributing to measurable carbon sequestration and improved aggregation, which reduce erosion, runoff, and vulnerability to drought and salinity stress. Multi-year experiments across cereal and horticultural systems demonstrate that INM maintains or increases crop yields while building SOC and soil quality indices, preventing nutrient mining and mitigating degradation associated with continuous chemical fertilization^[121]. Through the synergistic interaction of organic matter, microbial activity, and improved soil structure, INM creates a self-reinforcing soil-plant microbe system that enhances resilience, nutrient cycling efficiency, and long-term agricultural sustainability.

6. Impact of integrated nutrient management in horticulture and vegetable production on crop growth, yield, and quality

Integrated Nutrient Management (INM) significantly enhances crop growth, yield, and quality in horticultural and vegetable systems by ensuring balanced and sustained nutrient availability throughout the crop cycle. Across fruit and vegetable crops, integrated application of organic manures, mineral fertilizers, and biofertilizers consistently increases plant height, leaf area, branching, biomass, and yield components compared with sole NPK fertilization^[122]. In tomato, reduced NPK combined with vermicompost, FYM, and biofertilizers increased plant growth, fruit number, and yield per plant over 100% NPK alone^[123], while in cauliflower and bitter melon, integrated treatments (e.g., 75% RDF + FYM/vermicompost + *Azotobacter* + PSB)

produced the highest curd weight, fruit size, and total yield (13, 19). Strawberry and bitter melon studies report 10-190% higher yields under integrated organic-inorganic nutrient management due to improved fruit number and size (4, 5). Beyond yield, INM improves produce quality by increasing soluble sugars, vitamin C, protein content, β -carotene, total soluble solids, and micronutrient concentration, while reducing nitrate accumulation in crops such as tomato, strawberry, bitter melon, citrus, and lemon. Meta-analytical evidence further confirms that integrated nutrient strategies increase tomato yield and enhance fruit quality traits compared with mineral fertilizers alone. Improved physiological performance and nutrient balance under INM strengthen plant defense mechanisms, enhance tolerance to abiotic and biotic stresses, and improve nutrient use efficiency^[124]. Economic analyses in major vegetable crops demonstrate higher net returns and benefit-cost ratios under INM due to reduced fertilizer inputs and improved. Overall, INM in horticulture promotes sustained yield stability, superior nutritional and market quality, improved resource use efficiency, and long-term agroecosystem sustainability.

7. Environmental and economic implications of integrated nutrient management

Integrated Nutrient Management (INM) contributes significantly to sustainable agriculture by simultaneously reducing environmental risks and improving farm profitability through balanced use of organic, inorganic, and biological nutrient sources. By synchronizing nutrient release with crop demand and partially substituting chemical fertilizers with organic inputs, INM reduces nitrogen and phosphorus losses through leaching and runoff, thereby lowering risks of water pollution and eutrophication^[125]. The addition of organic amendments and residue retention increases soil organic carbon, microbial biomass, aggregation, and water-holding capacity, enhancing soil buffering and resilience against environmental stresses. Meta-analyses and long-term trials demonstrate that INM reduces reactive nitrogen losses, greenhouse gas emission intensity, and methane emissions in several cropping systems while maintaining comparable yield. Partial replacement of mineral nitrogen with farmyard manure or green manures improves soil carbon sequestration and lowers overall greenhouse gas intensity. Economically, INM enhances nutrient, water, and energy use efficiency, leading to higher yields, improved soil carbon stocks, and greater net returns compared with sole chemical fertilization^[118]. Studies across rice, rice-wheat, peanut-wheat, and horticultural systems report increased benefit cost ratios and farmer profitability under integrated approaches, even with reduced mineral fertilizer inputs. Improved soil health and nutrient buffering under INM enhance yield stability and resilience to drought and climatic variability, reducing production risks and supporting long-term income security. By integrating productivity, profitability, resource conservation, and environmental protection, INM strengthens agroecosystem services, supports circular nutrient use, and aligns with climate-resilient and sustainable agricultural development strategies.

8. Constraints and challenges in integrated nutrient management adoption

Despite its well-documented agronomic, environmental, and economic benefits, the large-scale adoption of Integrated Nutrient Management (INM) remains constrained by technical, socio-economic, and institutional barriers. Limited farmer awareness, inadequate technical knowledge regarding

appropriate nutrient combinations and timing, and weak extension support systems are consistently identified as major impediments to adoption. The perceived complexity of integrated systems and uncertainty about yield and profitability under diverse soil and climatic conditions discourage smallholders from implementation. Practical challenges such as inconsistent availability and variable nutrient composition of organic manures and biofertilizers, particularly in resource-poor regions, further limit effective nutrient planning. High labor requirements for collection, composting, and application of organic inputs, along with initial investment costs for composting units or biofertilizer production, act as additional economic barriers, especially for small and marginal farmers¹²⁶. Socio-economic factors-including limited access to credit, lower education levels, small landholdings, and weak farmer networks-also reduce adoption rates. Institutional gaps such as fragmented policy support, limited incentives for organic inputs, and reduced funding for soil fertility programs constrain scaling effort. Moreover, climatic variability, heterogeneous soils, and site-specific nutrient responses complicate management decisions and reduce farmer confidence in generalized recommendations. Collectively, these interconnected constraints highlight the need for stronger extension services, targeted financial incentives, improved input supply chains, farmer capacity building, and supportive policy frameworks to promote widespread and sustained adoption of INM practices.

9. Future perspectives and key research priorities in integrated nutrient management

Future research in Integrated Nutrient Management (INM) should prioritize long-term, system-level studies that integrate crop productivity, soil health, carbon sequestration, greenhouse gas mitigation, and economic performance across diverse agro-ecological regions^[127]. Greater focus is needed on understanding soil-plant-microbe interactions using advanced tools such as metagenomics and isotopic techniques to clarify nutrient cycling and stabilization mechanisms under integrated system. Developing climate-resilient and site-specific nutrient management strategies that address increasing climatic variability and extreme events is essential. Integration of precision agriculture technologies and decision-support systems with INM frameworks should be strengthened to enable real-time, efficient nutrient management^[128]. Additionally, long-term evaluation of emerging inputs such as nano-fertilizers, bio stimulants, and microbial consortia, along with improved nutrient recycling within circular economy models, is crucial for sustainable intensification. Socio-economic research and stronger interdisciplinary collaboration are equally important to ensure large-scale adoption and policy alignment of INM practices^[129].

10. Conclusions and policy implications

Integrated Nutrient Management (INM) provides a practical and sustainable framework to enhance crop productivity, nutrient-use efficiency, and long-term soil health in horticultural and vegetable systems. By integrating chemical fertilizers with organic manures, biofertilizers, and site-specific management practices, INM ensures balanced nutrient supply while supporting rhizosphere activity and microbial interactions that improve nutrient availability. Adoption at scale requires farmer awareness, access to quality inputs, soil testing, and supportive policies that encourage balanced fertilization and recycling of organic resources. Strategic investments in research, extension services, and policy integration are essential to mainstream

INM, positioning it as a cornerstone for sustainable agriculture, food security, and environmental resilience.

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