

Integrated Nutrient Management Strategies: Enhancing Soil Health, Productivity and Climate Resilience

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Abstract

Integrated Nutrient Management (INM) is a holistic strategy that combines inorganic, organic, and biological nutrient sources to optimize crop productivity while safeguarding long-term soil health and environmental sustainability. The principles of INM emphasize the balanced utilization of all nutrient sources, synchronization of supply with crop demand, and minimization of nutrient losses. Mineral fertilisers provide immediate nutrient availability, while organic amendments such as farmyard manure (FYM), crop residues, vermicompost, and fermented manures enhance soil organic matter (SOM), nutrient cycling, and microbial activity. Bio-fertilisers further strengthen nutrient availability through N fixation, P solubilization and K mobilization, and promotion of plant growth. Evidence across India's diverse agro-ecologies demonstrates that INM improves yields, profitability, and resource-use efficiency, while enhancing soil physical, chemical, and biological properties. Long-term experiments confirm that INM sustains crop productivity better than mineral fertilisers alone and contributes to soil C sequestration. Moreover, INM builds resilience to climate variability by enhancing plant tolerance to stress, improving soil water holding capacity (WHC), nutrient-use efficiency (NUE) of the system, with mitigation benefits *via* enhanced C sequestration and reduced greenhouse gas (GHG) emissions. Policy interventions such as subsidy reforms, manure quality regulation, research-extension linkages, and decentralized recycling infrastructure are essential to scale up adoption. Collectively, INM emerges as a pathway to climate-smart, resource-efficient, and sustainable agriculture in India and beyond.

Key words: Integrated nutrient management, organic and mineral fertilisers, bio-fertilisers, bio-stimulants, productivity, soil health, climate resilience

Introduction

Fertilisation, a vital component, is sustaining agricultural productivity. In traditional agriculture, organic sources of nutrients namely FYM, compost and green manure were the sole nutrient inputs. These C-rich amendments supported natural nutrient cycling and maintained soil health. However, they were bulky and slowreleasing, making them insufficient to meet the high nutrient demands of high-yielding Green Revolution varieties. Consequently, farmers increasingly shifted to mineral fertilisers, which delivered rapid and visible crop responses. While mineral fertilisers met short-term productivity goals that complete replacement of organic inputs combined with intensive cultivation led to a sharp decline in soil organic carbon (SOC), the key determinant of soil fertility (Padbhushan et al., 2021). This degradation of soil health, along with stagnation in FUE, posed a serious threat to the long-term sustainability of agricultural production as well as animal and human health. To address these challenges, the concept of INM came into existence in the latter half of the 20th century (Amanullah et al. 2023). INM is a holistic approach that integrates various organic and inorganic nutrient

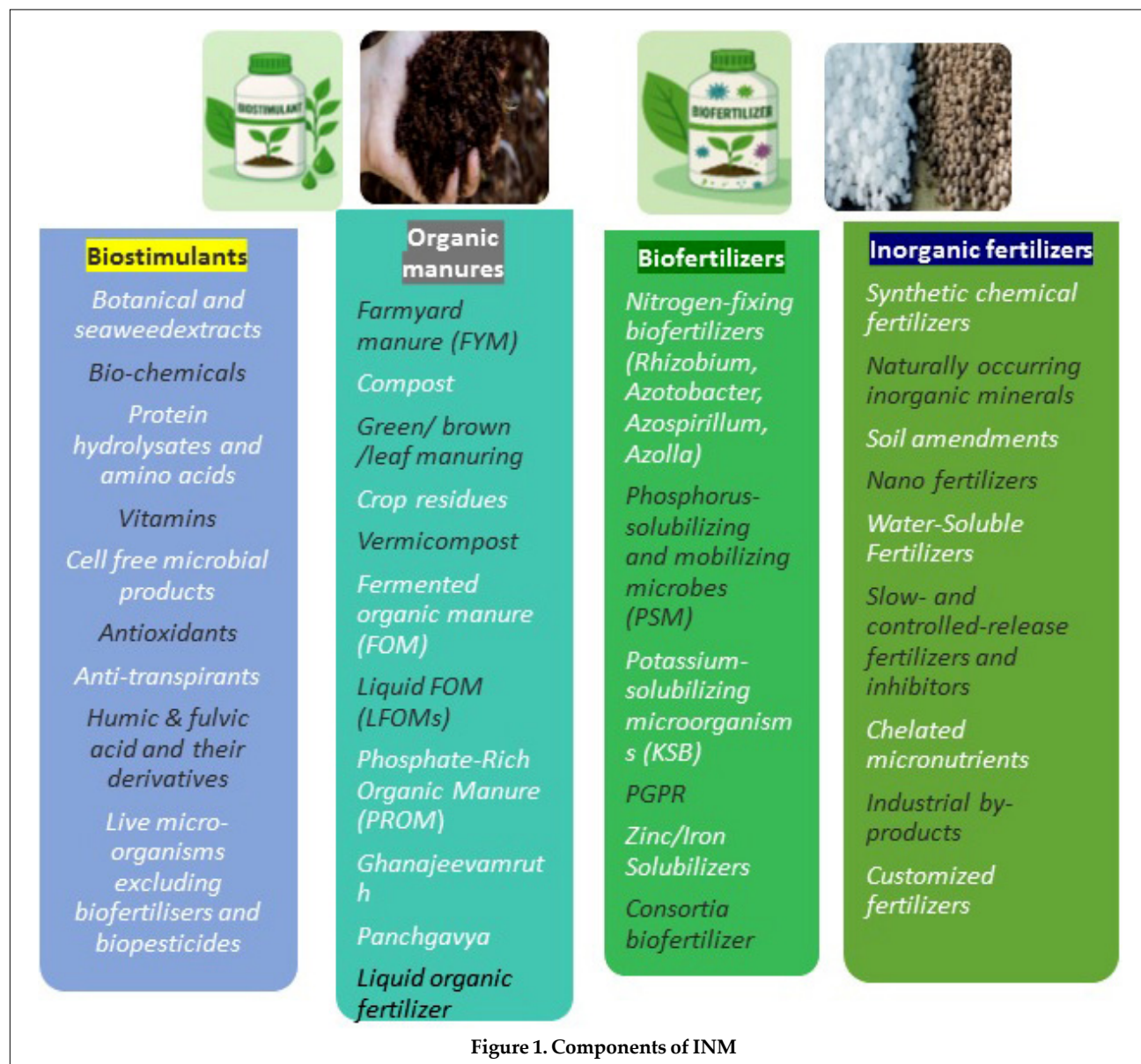
sources (FYM, compost, crop residues, green manures, bio-fertilisers, and bio-stimulants) along with cover crops and crop residues to provide balanced nutrition while preserving soil health. Unlike sole reliance on mineral fertilisers, INM feeds both the crop and soil, ensuring nutrient availability in the short-term and sustainability in the long-term (Amanullah et al., 2023). By increasing nutrient cycling, enhancing SOM buildup and strengthening the microbial diversity and structural stability of the rhizosphere, INM improves the soil's biological functioning and restores fertility. These enhancements boost the soil's ability to function as a biological system while also restoring its fertility. In addition, efficient uptake is ensured by timing N delivery with crop need, which maximizes productivity and reduces environmental nutrient losses. Furthermore, INM directly contributes to climate resilience by promoting C sequestration, decreasing reliance on energy-intensive fertilisers, and increasing water and nutrient use efficiency, which helps cropping systems better withstand stresses related to heat, drought, and unpredictable rainfall patterns (Graham et al., 2017). Mineral fertilisers supply the immediate needs of the crop, while the organic sources take care of the long-term

health and sustainability of production. This integration is crucial as the maximum potential of mineral fertilisers can be achieved only if the physical, chemical and biological properties of the soil are adequately maintained. Therefore, this article aims to review the role of INM in enhancing crop productivity, soil fertility, and NUE, while assessing its contribution to climate resilience and sustainable development goals (SDGs) such as SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Principles and Components of INM

INM is based on three major principles, such as, i) utilization of all the possible source of nutrients (both on-farm and off-farm) including bio-fertilisers to

optimize the input supply; ii) supplying the nutrient as per the crop requirement, accounting for both spatial and temporal variability in the demand; and iii) minimizing N losses from the soil and improving its use efficiency in the system (Wu and Ma, 2015). Collectively, these principles position INM as a holistic approach that integrates multiple nutrient sources to ensure both immediate crop performance and long-term sustainability. Adoption of INM reduces dependency on external inputs, rejuvenates degraded soils, enhances crop productivity, profitability, and resilience to climate stress, thereby contributing to the sustainability of farming systems. In India, with its diverse agro-ecological regions possesses vast resources to operationalize these principles effectively. The major components of INM are illustrated in **Figure 1**.



Mineral Sources of Fertilisers

Mineral Fertilisers. There are large number of such fertilisers in FCO 1985 and they supply nutrients predominantly in water-soluble forms, making them readily available to crops.

Naturally Occurring Inorganic Minerals: Minerals such as rock phosphate, polyhalite, glauconite, and waste mica act as slow-release nutrient sources, offering long-term benefits with minimal environmental risk. Application of rock phosphate with P-solubilizing microorganisms has shown yield advantages in crops such as wheat, green gram, potato, and maize (Biswas et al., 2022). Polyhalite is a rich source of S, K, Ca and Mg, while glauconite and waste mica can substitute conventional K fertilisers.

Soil Amendments: Soil amendments such as liming materials and gypsum are commonly used to correct acidic and alkaline soils, respectively. These amendments help bring soil pH closer to neutrality, enhancing nutrient availability. Liming materials include slaked lime, quick lime, ground limestone, basic slag, and dolomite are known to raise the soil pH by reacting with the H^+ ions to produce carbon dioxide and water. Gypsum not only alleviates soil alkalinity but also supplies Ca and S in plant-available forms. It also reduces subsoil acidity and improves soil structure, enhancing crop growth and yield. Phosphogypsum, a by-product of phosphatic fertiliser production, provides Ca, S, and P, and is a potential soil amendment, nutrient source, and can also be used for enriching organic manure. Slag-based gypsum (yellow gypsum), a byproduct of steel industry contains higher levels of S, Ca, P, Fe, Si and micro-nutrients compared to natural gypsum. Zeolite, a naturally occurring or synthetic porous mineral, acts as a slow-release fertiliser leading to higher NUE. When applied along with organic and mineral fertilisers, zeolite enhances nutrient uptake, increases yield, and significantly improving the soils' physio-chemical conditions and WHC.

Nano Fertilisers: Nano-formulations of N, Zn, and Cu, developed by IFFCO have demonstrated higher NUE compared to conventional fertilisers. Application of 75% recommended N dose combined with Nano-N and Zn sprays produced equivalent yields and profitability in cereals and oilseeds (Upadhyay et al., 2023).

Water Soluble Fertilisers: Water soluble fertilisers (WSFs) are ideal for the precise application nutrients including micro-nutrients through micro-irrigation as well as foliar spraying. Their complete solubility ensures uniform distribution, better nutrient uptake, and improved use efficiency, resulting in nutrient savings and higher yields. Foliar application elicits faster crop response than soil application, and

enhances crop metabolism, yield, and produce quality. Additionally, WSFs combined with other nutrient sources help mitigate drought stress and improve yields especially under dryland conditions (Asewar et al., 2021).

Slow and Controlled Release Fertilisers and Inhibitors: These products are designed to reduce N losses and provide a continuous supply of N throughout the season, thereby increasing NUE. Such fertilisers release nutrients gradually due to low solubility e.g., IBDU or chemical coatings e.g., sulphur-coated urea and polymer-coated urea. Urease inhibitors e.g., NBPT reduce urease enzyme activity, slowing urea hydrolysis to ammonium. However, nitrification inhibitors e.g., Nitrapyrin, DCD inhibit nitrosomonas bacteria while reducing ammonium-to-nitrate conversion. By flattening nitrogen release peaks, these products minimize losses, improve yields, and enhance NUE.

Chelated Micronutrients: Chelated micronutrients are formed by attaching micronutrients to unreactive organic molecules (chelating agents) to prevent precipitation or fixation in soil, increasing their bioavailability. EDTA is commonly used for Fe, Zn, and Cu. DTPA is preferred for slightly acidic to neutral soils, while EDDHA is most effective in alkaline and calcareous soils, particularly for Fe.

Industrial By-products: Several industrial by-products have crop nutritional value and increase the yield and profitability if utilized with necessary precautions. Basic steel slag, a byproduct of steel industry, contains Fe, Si, Ca, Mg, Mn, Na and K, helping in increasing the crop growth and productivity. Besides improving growth and yield, it has a liming effect, mitigates GHG emissions, and promotes C sequestration through mineral carbonation.

Customized Fertilisers: Customized fertilizers are multi-nutrient fertiliser products that are area and crop specific, developed as per the soil test-based recommendation, and validated using scientific crop models. Customized fertilisers ensure a balanced nutrition that increases growth, yield, profitability and NUE. Improved soil nutrient status and productivity of maize were observed with customized fertiliser application at Dindigul, Tamil Nadu (Kalaiselvi, 2016).

Organic Sources of Fertilisers

Farmyard Manure: Farmyard manure (FYM) is the most common source, prepared from decomposed dung, urine, bedding material, and leftover feed. On an average, it contains 0.5% N, 0.2% P O, and 0.5% KO. However, only about 30% N, 60–70% P, and 70% K become available to the first crop. Urine, rich in N and K, can be better utilized by spreading gypsum or single superphosphate in cattle sheds, which also

enriches FYM with P. Despite India's large bovine population and the huge potential for FYM production, poor infrastructure for collection, storage, and transport limits its use. Well-rotted FYM can be applied directly to crops, while partially decomposed manure should be incorporated two to three weeks before sowing (<https://agritech.tnau.ac.in>).

Green, Green Leaf and Brown Manuring: Green manuring is another important practice, which involves incorporating undecomposed green plant material into the soil. In-situ green manuring is done by growing leguminous crops including sun hemp, dhaincha, or cowpea until flowering, then ploughing them into the soil before sowing the main crop. In *ex-situ* green leaf manuring, green twigs of trees like gliricidia, karanj, neem, or gulumohar are collected and incorporated them into the field. Brown manuring, a more recent practice, consists of growing legumes such as sesbania along with the main crop and then knocking them down with herbicide to act as surface mulch. Brown manuring is compatible with no-till systems and reduces weed infestation while also saving water and fuel.

Crop Residue Management: Crop residues are also an important nutrient source, as they retain about 25%N and P; 50% S; and 75% K absorbed by the crop. India produces nearly 686 million MT of crop residues annually. Residues can be retained in fields as mulch, composted, or fermented into enriched manure. Using residues promotes nutrient cycling, sustains soil health, and reduces the harmful practice of residue burning. Residue used as cattle bedding absorbs urine amounting to two to three times their weight, thereby enriching N content. Residue can also be used as feedstock for composting, making them nutritionally rich. Moreover, studies have also proved that residue retention in the fields maintains crop yields even under reduced fertiliser application, confirming improvements in soil fertility.

Vermicompost: Vermicomposting involves utilization of earthworms and associated microorganisms to decompose OM to produce vermicompost (VC), a nutrient-rich fertiliser, also known as worm castings. Nutrients in VC vary depending on the quality and composition of the organic feedstock and the complexities of the vermicomposting process, but in general, it contains all most all the vital plant nutrients. Application of VC improves soil structure by decreasing bulk density, enhancing the hydraulic conductivity, aeration, moisture retention, and root penetration (Rehman et al., 2023). Apart from adding nutrients and beneficial microorganisms to soil, VC also reduces the C-to-N ratio of the soil, thereby, increasing the plant available nutrient pool. VC also supplies certain vitamins and other beneficial compounds that enhances crop productivity and

quality, as well as plant health.

Fermented Organic Manure: Fermented organic manure (FOM), produced in biogas plants, is another emerging source. It contains around 1.2% NPK and 14% OC along with beneficial microorganisms. Its application, particularly when combined with mineral fertilisers, improves soil health without reducing yields. As of now, India produces an around 1 million MT of FOM per annum and its effective utilization as manure can decrease the dependency on agricultural imports. Yadu et al. (2025) reported that application of 1.0 to 3.0 t ha⁻¹ FOM along with the remaining dose of RDF through fertilisers resulted in statistically similar yield of rice to that obtained with RDF applied fully through fertilisers or when 2.5 to 5 t ha⁻¹ FYM along with remaining dose of RDF through fertiliser was applied.

Liquid Fermented Organic Manure: Liquid fermented organic manures (LFOM) are nutrient-rich slurries with about 1.2% NPK, 14% OC, and 90–97% moisture, making them suitable for foliar application and fertigation. They provide readily available nutrients, enzymes, and beneficial microbes, thus improving plant metabolism. LFOM is produced as slurry byproduct in compressed biogas plants and is approved for marketing by the Government of India. Traditional Indian formulations such as Kunapajala, Panchagavya, Jeevamruth, and Amritpani have long been used for improving soil fertility and crop productivity, are also examples of liquid fermented organic manures.

Phosphate Rich Organic Manure: Phosphate-rich organic manure (PROM) is obtained by composting low-grade rock phosphate with organic sources such as FYM, pressmud, or crop residues. Organic acids released during decomposition solubilize P from rock phosphate, thereby improving its availability to plants. P solubilizing microorganisms further enhance this effect. FOM can also be fortified with P minerals to produce PROM. Integrated use of RP-enriched composts with 50% of the recommended NPK fertilisers is found to significantly increase wheat and green-gram yields compared to sole compost or mineral fertiliser applications (Moharana and Biswas, 2022). Other organic amendments include bio-enriched manures fortified with beneficial microbes, bone meal (a slow-release source of Ca and P), red algae-derived potash (a renewable source of K), and biochar or composted animal waste (egg shells, oyster shells, chicken litter, etc.). These materials improve nutrient cycling, enhance microbial activity, and in some cases, help mitigate heavy metal toxicity in soils through adsorption and chemisorption. Together, these organic nutrient sources form the backbone of INM, ensuring balanced nutrition, reduced dependency on fertilisers, improved soil health, and

resilience in agroecosystems.

Bio-fertilisers: They are an essential part of INM systems because they are sustainable, economical, and environmentally benign substitutes for synthetic inputs. By transforming atmospheric N into the forms that plants can use. N-fixing bio-fertilisers like *Rhizobium*, *Azospirillum*, *Azotobacter*, and the symbiotic water fern *Azolla* improve soil fertility and lessen the need for conventional N fertilisers. Microorganisms that mobilize and solubilize P are equally significant because they increase P availability in the soils, thereby improving crop uptake efficiency. In a similar way, K-mobilizing bio-fertilisers help plants tolerate stress and maintain a balanced diet by releasing bound K from the soil minerals. Apart from these, use of Zn solubilizing bacteria, mycorrhizal bio-fertilisers, carrier and liquid-based consortia, P solubilizing fungal bio-fertilisers, etc. can also improve available nutrient status of the soil.

Bio-stimulants: They are a more recent addition to the concept of INM that can lead to agricultural production resilience. Bio-stimulants are the substances of natural or synthetic origin, or microorganisms, or their different combinations. They stimulate or enhance the natural processes in the plant as well as soil, improving crop production and resource use efficiency. They include botanical, extracts of seaweeds such as *Gracilaria*, *Kappaphycus*, *Sargassum*, and *Turbinaria*, etc; bio-chemicals such as chitosan, salicylic acid, etc.; protein hydrolysates and amino acids such as soy protein hydrolysate, L-tryptophan, etc; vitamins; cell-free microbial

products such as siderophores, gibberellins, yeast extract filtrates, etc.; antioxidants; anti-transpirants; humic & fulvic acid and their derivatives such as potassium humate; live micro-organisms such as *Trichoderma harzianum*, *Pseudomonas fluorescens*, *Bacillus subtilis*, etc. excluding bio-fertilisers and biopesticides (www.pib.gov.in/PressReleasePage.aspx?PRID=2165081). Bio-stimulants enhance plant physiological processes such as germination, photosynthesis, root growth, defence mechanism, stress tolerance, biosynthetic pathways, etc., while also stimulating higher microbial activity in soil that ultimately enhances its nutrient and water supplying capacity. Their application results in a fertile soil, healthy crop and a resilient production system characterized by higher productivity, produce quality, resource use efficiency, and yield sustainability. Though not a direct source of nutrient, bio-stimulants help in better realization of the genetic potential of the crops.

INM with Crop Productivity, Soil Health and Climate Resilience

INM and Crop Productivity: Combined application of mineral and organic fertilisers known as INM not only provides a balanced nutrition to the crop, but also enhances the soil health, thereby increasing yield as well as produce quality on sustainable basis (Figure 2). In rice-wheat (RW) systems across India, INM resulted in yield increases of 1.2–28.1 and 4.5–39.2% in rice and wheat, respectively over inorganic or organic treatments (Sharma et al., 2019). Similarly, meta-analysis reported 1.4 and 4.9% yield increases

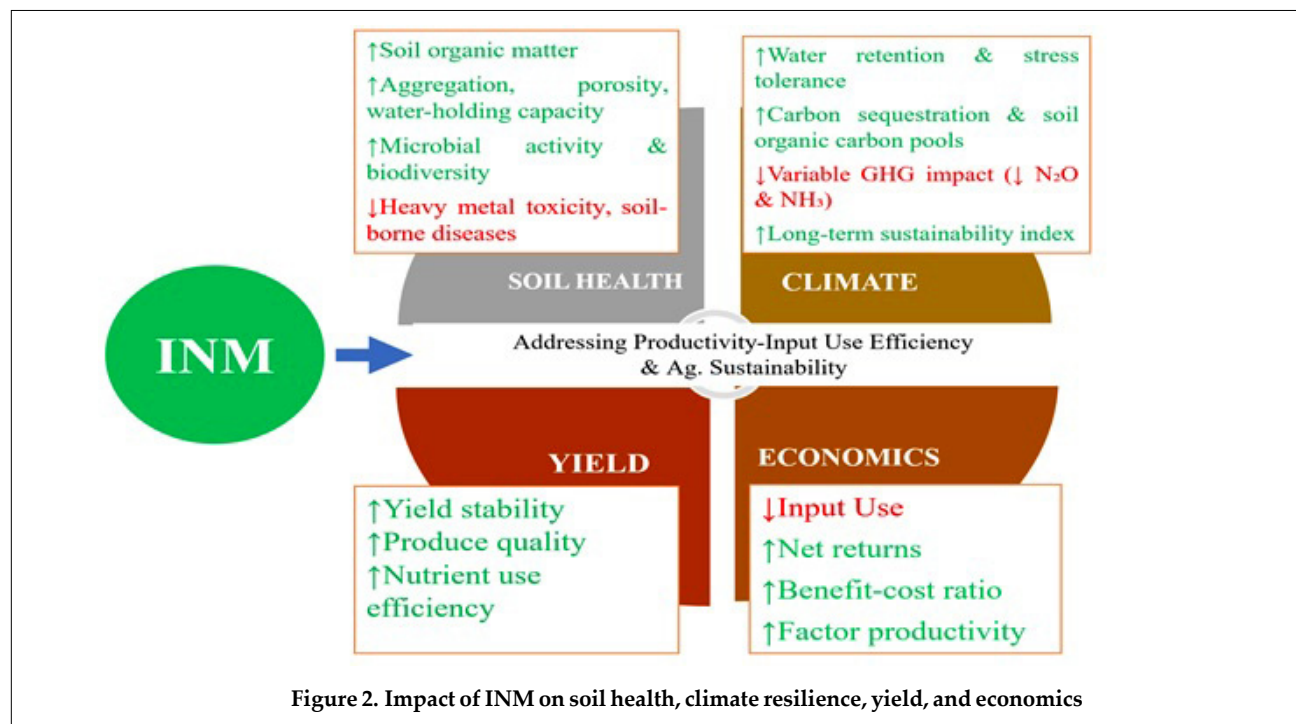


Figure 2. Impact of INM on soil health, climate resilience, yield, and economics

in rice and wheat, respectively, when organics such as FYM, VC, green manuring, and bio-fertilisers were integrated with mineral fertilisers (Padbhushan et al., 2021). Moreover, INM enhances nutrient cycling, improving nutrient availability and use efficiency, which decreases the need for external fertilisation in subsequent years. AICRP on long-term fertiliser experiments conducted across the country, covering major soil types and cropping systems, showed that sustainability yield index (SYI) and soil health are higher under INM (NPK+FYM) than mineral fertilisers alone (Singh et al., 2019). Organic manures, an integral component of INM (Table 1), also have ameliorative effects on soil pH, and application of FYM at 5 t ha⁻¹ gave better economic returns than lime application in acidic soils of Ranchi (Singh et al., 2019). In the North Eastern parts of India, INM combining mineral fertilisers, organics, bio-fertilisers, and lime is a key component of improved agronomic management practices designed to improve sustainability and profitability of upland crops such as direct-seeded rice and maize under jhum cultivation (Kharlukhi et al., 2024). However, relative crop response to INM depends on soil properties and crop management. Multi-location trials showed that significant improvement in high-quality protein maize (HQPM) yield under INM was limited to soils with lower OC and initial N availability (Jat et al., 2013).

INM impact is generally more pronounced in loamy soils than in clayey soils, due to better soil aeration and drainage, which led to higher increases in SOC and microbial quotient (Padbhushan et al., 2021). It has also been shown to be equally beneficial in irrigated and rainfed ecosystems. In Alfisols of Anantapur, substituting 50% N with FYM or using 100% N with two nights of sheep penning gave similar yields of rainfed groundnut as conventional methods, regardless of protective irrigation (Swamy et al., 2021). In most of the experiments' reports, there has been increases in yield and better quality and economics under INM. However, a few studies observed marginal decreases also. For example, potato grown in Gajapati district of Odisha, application of 90% RDN + 10% N through vermicompost or FYM resulted in a lower economic return compared to conventional practice, even though tuber yield, starch content, and carbohydrate content were statistically similar (Prakash et al., 2025). Across various crops including maize, rice, chickpea, lentil, sugarcane, and oilseeds, INM has consistently demonstrated yield improvements, along with higher net returns and enhanced crop quality (Table 1).

INM and Soil Health Leading to Higher Sustainability:

INM plays a pivotal role in maintaining good soil health which is the key to long-term agricultural sustainability. OM acts as cementing material

between soil particles and improves soil aggregation, porosity and WHC while reducing the soil penetration resistance. OM rich soils also have higher ion retention and buffering capacity, leading to pH optimization and better availability of nutrient. Moreover, the added C serves as a source of energy for soil biome, increasing their activity and nutrient cycling. Macro-organisms such as earthworm, millipedes and arthropods are also benefited for change in the soil properties under INM, thereby contributing to better physical, chemical and biological properties of the soil (Table 2). Borase et al. (2020), based on their study on four different cropping systems, reported that INM resulted in significant reduction in soil microbial quotient, which implies a more stable and efficient soil microbiome- an indicator of sustainability. Additionally, OM addition helps in alleviating heavy metal toxicities and soil borne diseases. FYM application is known to decrease phyto-availability of heavy metals such as Pb, Cd, Zn, Cu, Mn, Ni and Cr to beetroot under waste-water irrigated conditions (Singh et al., 2010). *Neem* cake, a good source of plant nutrients, also act as nitrification inhibitor, soil conditioner and antibiotic to soil borne pathogens. Composts made from different sources can be inoculated with biocontrol agents to suppress the soil borne pathogen, facilitating better crop performance. Moreover, though generally weed plants also get benefitted from the increased fertility under INM, certain organic sources may have allelopathic effect on the weed population, leading to a potential decrease weed dynamics (Ghosh et al., 2020).

INM and Climate Resilient Agriculture: With climate change posing serious challenges to agriculture, INM has emerged as a cornerstone strategy for building resilience. Strategic use of nutrients from diverse sources under INM not only sustains productivity but also supports both adaptation and mitigation to climate stress. Increased yields, higher resource use efficiency, and greater tolerance to drought, flood, and other abiotic and biotic stresses make INM a vital tool for adaptation. Improved soil properties under INM, such as enhanced WHC and infiltration rate, further strengthen resilience against moisture stress. It also induces physiological and biochemical changes that improve stress tolerance in crops. Application of vermicompost and bio-agents has been shown to decrease leaf proline content and canopy temperature while increasing antioxidant enzyme activity, leaf water content, and membrane stability in mustard, indicating better drought adaptation (Mamnabi et al., 2020). Long-term application of FYM or lime along with NPK over 47 years resulted in soil microbial communities with greater tolerance to moisture stress (Vishwanath et al., 2025). Similarly, seed inoculation with vesicular arbuscular mycorrhizal fungi enhances root volume for water uptake, increases P and Zn

Table 1. Effect of INM on crop productivity across cropping system

Crop/ CS	INM practice	Control	Yield increase	Economics/ crop quality	References
Rice	<i>Panchagavya</i> application: Seedling root dip + 6% FA + application with irrigation water	No application	GY ↑ 37.2%	Energy productivity ↑ 30.8%	Upadhyay et al., 2022
Wheat	Soaking of seed for 8 hrs. in 25 different herbal extracts	No seed treatment	<i>Phyllanthus emblica</i> extract: Seedling length ↑ 2.33%, weight ↑ 2.20%	Phenol ↑ 2.32%; flavonoid ↑ 2.05% and chlorophyll ↑ 4.11% in seedling	Yadav et al., 2024
	SynBio1 (SM + HA)	Un-inoculated control	GY ↑ 67.83%; Germination % ↑ 28.4%	Chlorophyll content ↑ 24.8	Pathak et al., 2024
	SynBio1 (SM + HA)	Un-inoculated control	GY ↑ 55.8%; Germination % ↑ 22.2%	Chlorophyll content ↑ 14.2	
	FA of Glycine betaine under drought stress in 19 genotypes	No Glycine betaine application under stress	Avg. GY ↑ 28.0%		Gupta and Thind, 2017
Rice- wheat	INM	Inorganics (IORA) & Organics only (ORA)	Rice: ↑ 1.2–28.1%, Wheat: ↑ 4.5–39.2%	-	Sharma et al., 2019
	50% RDF + 50% N through GM or FYM or paddy straw to rice; 100% RDF to wheat	100% NPK fertilisers	↑ 8.37–8.52 t/ha	-	Meta analysis Saha et al., 2019
	PM application at 6.25 t ha ⁻¹ with mineral fertiliser in rice	No PM application	Rice: 63.7–64.8%, Wheat: 23.9–24.6%	-	Kaur et al., 2023
Rice-rice	75% RDN through NCU + 25% RDN through FYM	100% RDN through NCU	↑ 4.4 to 5.1% higher GY	↑ 17.8% NR	Paramesh et al., 2023
	50% RDN fertilisers + 50% RDN as GM of Azolla in <i>kharif</i> ; 100% RDN fertiliser in <i>rabi</i>	100% NPK chemical fertilisers	↑ 6.9% GY	-	Mishra et al., 2017
Rice-chickpea	75% NPK + FYM @ 5 t ha ⁻¹ year ⁻¹ (rice) + Bio-fertiliser BGA in rice, Rhizobium in chickpea and PSB was applied at 3–5 kg ha ⁻¹ in both the crops.	100% NPK; 100:60:40 and 20:60:20 (N: P ₂ O ₅ : K ₂ O) kg/ha- rice and chickpea, respectively	Rice: ↑ 7.3%, Chickpea: ↑ 10.6%	-	Thakur et al., 2023
Rice- potato-blackgram	75% RDF +15% FA- <i>Gracilaria</i> sap	100% RDF	Wheat GY ↑ 27.5%; NR ↑ 59.0% Potato TY ↑ 32.0%; Urd SY ↑ 50.0%.		Pramanick et al., 2018
	75% RDF +15% FA- <i>Kappaphycus</i> sap		Wheat GY ↑ 26.0%; NR ↑ 54.4% Potato TY ↑ 29.8%; Urad SY ↑ 32.0%.		
Maize	100% RDPK + 75% RDN +25% N through <i>Brassicaceous</i> seed meal	100% RDNPK maize yield	Up to 22.3% NR ↑ 7.8%; EE ↑ 7.7%		Ghosh et al., 2020
Maize-wheat	50% RDF + 50% N through FYM in <i>kharif</i> ; 100% RDF in <i>rabi</i>	100% RDF in both <i>kharif</i> and <i>rabi</i> seasons	Maize GY ↑ 13.8–64.8%, Wheat: ↑ 23.9–24.6%	-	Manjhi et al., 2014
Fodder maize – cowpea intercropping	75% RDF through inorganic + Zn + PGPR+ FYM	100% RDF through inorganic + Zn	↑ 10.7 % green fodder yield	17.9% CP, ↑ Fe, Zn, Mn, Cu	Yadav et al., 2022
Mustard	75% RDF + 40 Kg S + VC at 5 t ha ⁻¹ + Azotobacter + PSB	RDF (N, P, K) @80:40:40 + 40 S kg/ha	↑ 12.7% seed yield	+9.0% higher protein content	Chandan et al., 2019

Table 1. Effect of INM on crop productivity across cropping system

Crop/ CS	INM practice	Control	Yield increase	Economics/ crop quality	References
Groundnut	Soil application of 1250 kg <i>Ghanajeeva-mrutha</i> + <i>Jeevamrutha</i> 3000 L ha ⁻¹	Recommended NPKZnB, Gypsum, FYM	Statistically similar PY (↑ 2.7%)	-	Veeranna et al., 2023
Green gram	RDF + RST + seed soaking and one FA of Sagarika (sea weed extract)	RDF + RST	GY ↑ 17.3%	NR ↑ 27.8%	Alagundagi, 2020
Soyabean	50% RDF + 5 t ha ⁻¹ PM	100% RDF: 30-26.2-33.2 NPK kg ha ⁻¹	↑18.6% GY	↑ 26.6% NR + 25.1% higher EE	Singh et al., 2013
Lentil	50% RDN +100% RDP + VC @ 1 t ha ⁻¹ 50% RDN + 100% RDP + VC @ 1 t ha ⁻¹ + 0.5% ZnSO ₄ 50% RDN + 100% RDP + VC @ 1 t ha ⁻¹ + 0.5% FeSO ₄ 50% RDN + 100% RDP + VC @ 1 t ha ⁻¹ + 0.5% ZnSO ₄ + 0.5% FeSO ₄	RDF: N - P ₂ O ₅ ; 20 - 40 kg ha ⁻¹	↑15.6-23.5% SY	-	Kumar et al., 2022
Linseed	75% RDF + 2.5 t ha ⁻¹ VC	100% RDF	↑15.3% fibre yield	8.6% ↑ fibre quality	Kumar et al. (2019)
Sugarcane	75% RDN through inorganic + 25% RDN through FYM + <i>Azotobacter</i> + <i>Azospirillum</i>	100% RDN through inorganic	↑ 30.9% cane yield	↑ 4.9% higher brix reading, 5.0% sucrose content	Banerjee et al. (2018)
Cotton	50% N + 2.5 Mg Phospho-compost + 5 Mg FYM	100% N	↑ 28.4 % higher seed cotton yield	-	Reddy et al. (2017)
INM – Integrated nutrient management; IORA – Inorganic only recommended application; ORA – Organic only recommended application; RDF – Recommended dose of fertilisers; RDN – Recommended dose of N; RDP – Recommended dose of P; RDK – Recommended dose of K; RDNPk – Recommended dose of N, P, K; RDNPkSZnB – Recommended dose of N, P, K, S, Zn, B; PM – Poultry manure; FYM – Farmyard manure; VC – Vermicompost; BGA – Blue green algae; PSB – Phosphate solubilizing bacteria; PGPR – Plant growth promoting rhizobacteria; NCU – <i>Neem</i> coated urea; EE – Economic efficiency; NR – Net returns; CP – Crude protein; GY – Grain yield; SY – Seed yield; SM – Synthetic microbial community; HA - Humic acid; FA - Foliar application; TY - Tuber yield; RST – Recommended seed treatment; PY – Pod yield					

absorption, and also triggers physiological adjustments that strengthen drought adaptation. Beyond adaptation, INM plays a critical role in climate change mitigation by influencing C sequestration and greenhouse gas emissions. OM addition promotes higher percentage of soil macro-aggregates, within which C remains protected from microbial degradation, ensuring long-term stability (Table 2). Long-term INM in RW systems has been reported to increase micro-aggregates within macro-aggregates, thereby enhancing C storage in more stable soil fractions (Das et al., 2014). INM also enriches both active and passive C pools, suggesting improved biological activity along with higher long-term C sequestration potential (Anandakumar et al., 2022). Substituting 50% of NPK with FYM or green manure in rice–wheat systems has been found to raise the

sustainability index, SOC, microbial biomass carbon, particulate organic carbon, and mineralizable C, thereby enhancing sequestration and system sustainability (Nayak et al., 2012).

Notably, these benefits are greater in humid and clayey soils compared to semi-arid regions with sandy soils. However, influence of INM on GHG emissions remains complex and sometimes contradictory. Mohanty et al. (2020) observed that while INM reduced NO and NH emissions in rice–rice systems at Cuttack, it also increased methane flux, leading to a higher overall GHG intensity compared to mineral fertilisation. Therefore, there is a trade-off between C sequestration and GHG emissions under INM. Yet, they also noted that C sequestration increased at a higher rate per unit of CO emitted under INM, indicating improved C stability. However, some studies also

report reduction in the GHG emissions with INM adoption (Table 2).

Policy and Institutional Role in Supporting INM Adoption and Dissemination

Widespread adoption of INM depends heavily on supportive institutions and enabling policies. A cohesive framework that integrates agricultural policy, research, extension, markets, and community participation is essential for large-scale implementation (Figure 3). Policy frameworks play a critical role through reforms in fertiliser subsidies, incentive programs, and regulatory mechanisms. Conventional fertiliser subsidies often promote the overuse of mineral fertilisers. Redesigning these subsidies to include compost, bio-fertilisers, and organic manures can ensure parity across nutrient sources. Incentives such as direct benefit transfers, C credit programs, or payments for ecosystem services can reward farmers who adopt INM for enhancing soil health and contributing to climate mitigation. At the same time, regulatory mechanisms are needed to standardize composts, bio-fertilisers, and recycled organics, ensuring quality assurance and building farmer's trust. Organizational structures for research and innovation also need reform. Institutions such as Consortium of International Agricultural Research Centers and the Indian Council of Agricultural Research are pivotal in developing location-specific INM packages suited to diverse soil types, crops, and climates. ICT-based platforms, Krishi Vigyan Kendras, and Farmer Field Schools can bridge the gap between scientific knowledge and field practices. Participatory approaches can encourage local ownership and strengthen adoption. Public-private partnerships can further support the last-mile delivery of micronutrients, compost, and bio-fertilisers by improving supply chains in collaboration with private companies and NGOs (Figure 3).

Market and infrastructure support are equally important for scaling INM. Building supply chains for organic inputs, establishing decentralized bio-fertiliser manufacturing hubs, composting facilities, and biomass collection centres can ensure availability of quality inputs. Financial support through credit access, crop insurance, and startup assistance can encourage entrepreneurship in INM input production. Value addition through certification of sustainable or organic produce can increase market value, motivating farmers to adopt INM practices. Decentralized governance systems such as panchayats, cooperatives, and farmer producer organizations can play an effective role in nutrient recycling by utilizing livestock manure, crop residues, and municipal compost. Multi-stakeholder knowledge platforms linking farmers, scientists, policymakers, and private players are essential to scale up INM in an evidence-based manner. Integrating INM

promotion with soil health missions, Sustainable Development Goals (SDGs), and nationally determined contributions can align resources and ensure synergy with broader sustainability agendas.

Future Perspectives

The future trajectory of INM will depend on combining technological innovation, sustainability goals, and farmer-centered practices (Figure 4). Although current evidence confirms INM's benefits in soil health, productivity, and climate adaptation, scaling requires multifaceted strategies. Key perspectives include:

Policy Support: Fertiliser subsidy reforms, quality assurance standards for bio-inputs, and alignment with soil health and climate missions are essential to scale INM.

Bio-input Innovation: Focus on site-specific bio-fertilisers tailored to crop–soil–climate conditions, Nano fertilisers, and microbial consortia can significantly improve NUE.

Improved Quality of Input Manure: Standardization and quality enhancement of FYM, compost, and vermicompost will ensure consistent nutrient availability and reduce nutrient losses. Gypsum/SSP fortification and compost enrichment can raise their fertiliser value.

Recycling of CBG Plant Waste: Solid and liquid by-products from compressed biogas (CBG) plants can be recycled as fermented organic manure (FOM) and liquid fermented organic manure (LFOM). This closes nutrient loops, reduces dependence on imported fertilisers, and provides an eco-friendly alternative.

Liquid Organic Manure: Adoption of LFOMs like jeevamruth, panchagavya, and CBG slurry promotes foliar feeding and fertigation. Rich in enzymes, plant hormones, and microbes, they enhance soil health, nutrient uptake, and crop productivity.

Climate-smart Strategies: INM regimes combining organics, bio-fertilisers, and balanced chemicals improve water-use efficiency, boost N efficiency, increase soil C sequestration, and help crops withstand abiotic stresses like drought.

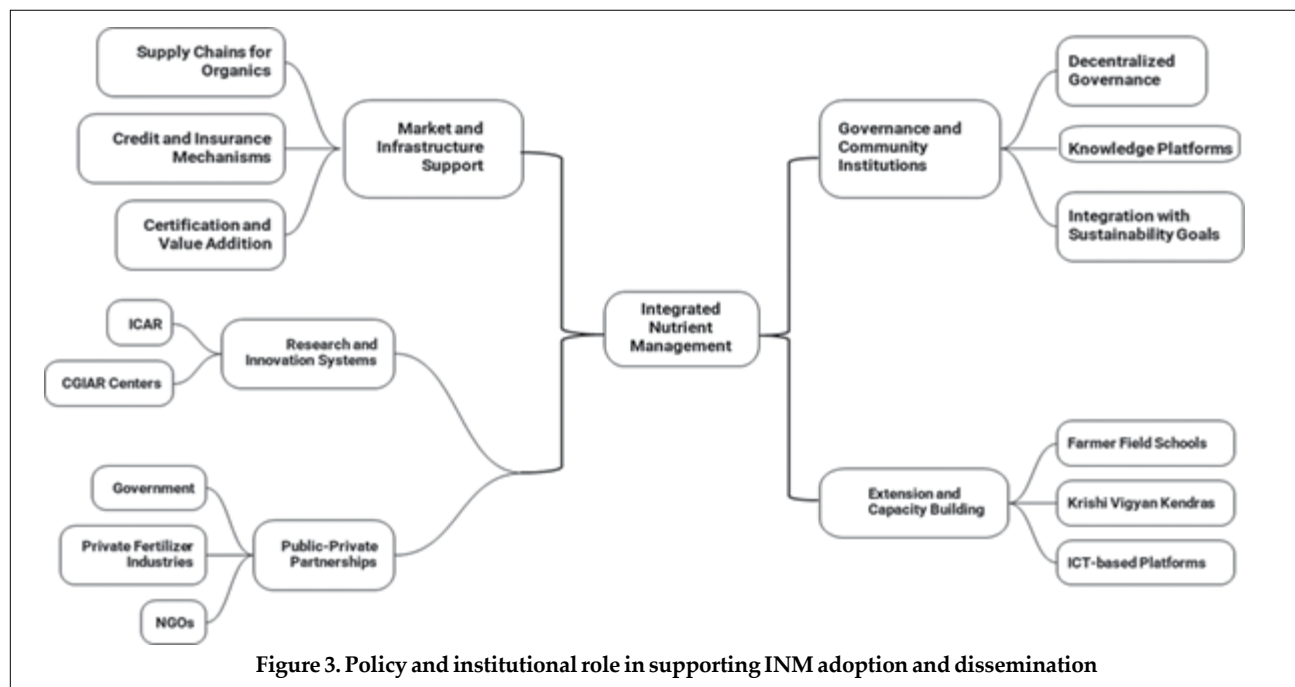
Digital Tools: AI-enabled soil testing, nutrient budgeting, mobile advisory services, and precision fertigation systems enable farmers to make data-driven, site-specific nutrient management decisions.

Socio-economic Inclusion: Integration of local knowledge, gender-sensitive participation, and farmer cooperatives fosters wider adoption. Community-level composting units and FPO-led input supply chains will support local ownership.

Long-term Assessment: Continuous monitoring, life-cycle assessments, and multi-location trials will

Table 2. Effect of INM practices on the soil health

Crop	INM practice vs. control	Effect on physical properties	Effect on chemical properties	Effect on biological properties	References
Rice	<i>Panchagavya</i> : Seedling root dip + 6% FA + with irrigation water vs. no application			MBC ↑33.5%; DHA ↑57.7%; Urease ↑ 71.6%	Upadhyay et al., 2022
RR	75% N (NCU) + 25% N (FYM) vs. 100% N (NCU)	-	Av. N, P, K ↑30.1%, 41.0%, 10.8%	MBC ↑51.3%; DHA ↑117.1%; Urease ↑106.3%; Phosphatase ↑19.5%	Paramesh et al., 2023
RW	50% RDF + 50% N FYM (rice) + 100% RDF wheat . 100% RDF	EC ↑10%	SOC ↑13.8%; Available Zn ↑1 46.6%; Cu ↑53.8%; Fe ↑25.8%; Mn ↑29.3%; B ↑23%	-	Saha et al. 2019
	50% RDF + 50% N FYM (rice) + 100% RDF (wheat) vs. 100% RDF	BD ↑6.8%	SOC ↑44.6%; C pool index ↑36.4%; ↑C-sequestration; ↑GHG emission intensity		Ranjan et al., 2023
	Organic (FYM, VC, GM, BF) + Inorganic vs. 100% NPK	Bulk density ↑4%	Av. N ↑9.3% in control; Av. P & K ↑8.2% & 3.5% in INM; SOC ↑23.2% (rice), 16.2% (wheat)	MBC ↑55.9% (rice), 32.9% (wheat); MQ ↑26.5% & 14.4	Padbhushan et al., 2021 Meta analysis
MMu	50% NPK + lime + BF + FYM vs. 100% NPK	Water stable aggregates ↑21.6%; Porosity ↑13.1%; WHC ↑17.2%; Infiltration ↑80.4%	OC ↑17.8%; pH ↑16.7%; Av. N ↑31.6%; Av. N ↑31.6%; Av. P ↑23.7%; Av. K ↑6.1%	Av. N ↑31.6%; Av. P ↑23.7%; Av. K ↑6.1%; MBC ↑28.4%; MBN ↑12.0%; MBP ↑14.4%	Saha et al., 2010
MW; MW-	(Long-term) 50% NPK + CR + FYM + BF vs. RDF NPKSZnB	Macro-aggregates ↑19.7%; Micro-aggregates ↑29.5%	TOC ↑18.7%; Labile C ↑50.4%; C management index ↑	C associated with aggregates ↑9.4–20.9%	Hazra et al., 2019
Lentil	RDN + ZnSO + Rhizobium + PSB + PGPR + Mo vs. RDN only	Nodules ↑35.9%; Leghaemoglobin ↑64.7%			Singh et al., 2018
Tulsi	<i>Jeevamrit</i> (500 t ha ⁻¹) + FYM (7.5 t ha ⁻¹) vs. RDF <i>Kunapajala</i> (500 t ha ⁻¹) + FYM (7.5 t ha ⁻¹) vs RDF	BD ↑2.5%; BD ↑1.9%;	SOC ↑13.0%; Av. N, P & K ↑ 6.6, 21.6 & 2.8% SOC ↑13.0%; Av. N, P & K ↑ 8.9, 23.2 & 4.6%	Total microbial count ↑ 203.4 % Total microbial count ↑ 130.4 %	Yadav et al., 2024
RW = Rice–wheat; RR = Rice–Rice; MW = Maize–wheat; MW–Mb = Maize–wheat–Mungbean; MW–MC = Maize–wheat–maize–chickpea; PP–W = Pigeonpea–wheat; RDF = Recommended dose of fertiliser; RDN = Recommended dose of N; FYM = Farmyard manure; VC = Vermicompost; GM = Green manure; BF = Bio-fertiliser; CR = Crop residue; BD = Bulk density; SOC = Soil organic carbon; MBC = Microbial biomass carbon; MBN = Microbial biomass N; MBP = Microbial biomass P; DHA = Dehydrogenase activity; MQ = Microbial quotient; EC = Electrical conductivity					

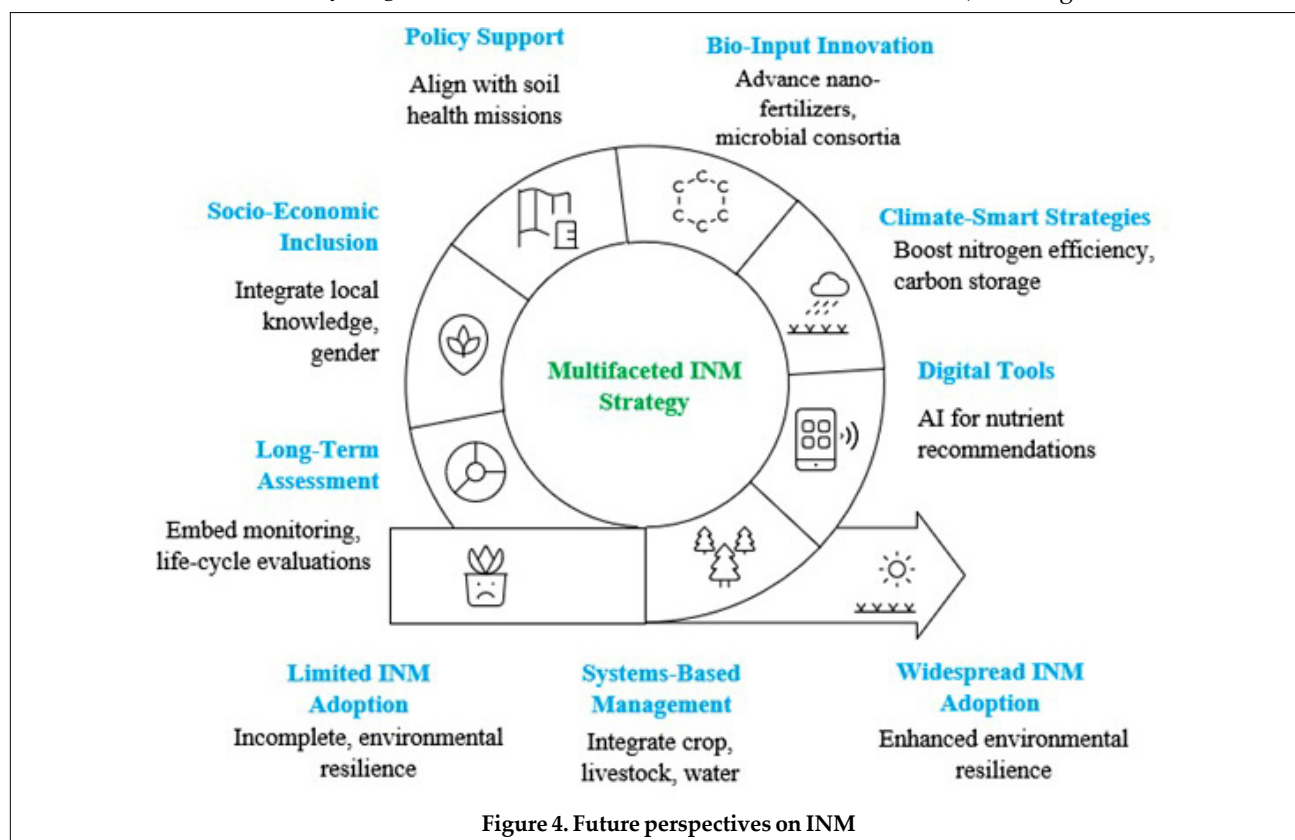


validate INM's productivity, climate, and livelihood benefits, providing evidence for large-scale policy adoption.

Systems-based Management: Future INM must link crops, livestock, forestry, and waste recycling into a circular nutrient economy. Agricultural residues,

municipal organic waste, and CBG slurry can be converted into safe fertilisers, boosting resilience.

Widespread INM Adoption: With stronger institutional and infrastructural support, INM can deliver sustainable productivity, profitability, and environmental resilience, making it a cornerstone of



climate-smart agriculture.

Conclusion

Integrated Nutrient Management offers a holistic pathway to sustainable agriculture by simultaneously enhancing soil health, crop productivity, and climate resilience. Through the balanced integration of organics, bio-fertilisers, and mineral inputs, INM sustains productivity, profitability, and quality while improving soil structure, microbial activity, and nutrient cycling. Long-term experiments confirm that INM not only maintains but also stabilizes yields and soil fertility better than exclusive reliance on mineral fertilisers. By improving nutrient- and water- use efficiency, INM reduces dependency on external inputs and strengthens resource security for farmers. Although trade-offs in GHG emissions remain context-specific, INM contributes to C sequestration and bolsters adaptation to climatic shocks. As a triple-benefit approach supporting production, sustainability, and resilience, INM must be scaled up through farmer-centric innovations, precision technologies, efficient input supply chains, and enabling policies. Strong institutional support, public-private partnerships, and decentralized nutrient recycling systems are equally critical. Establishing INM as a cornerstone of resilient agroecosystems is essential to ensure long-term food, nutritional, and environmental security.

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