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An assessment of integrated nutrient management as a climate-smart approach to sustainable soil health and agricultural productivity

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Abstract

The rapid increase in global population has significantly intensified the demand for food production, necessitating the adoption of sustainable agricultural practices. Integrated nutrient management (INM) combines inorganic fertilisers, organic amendments and biofertiliser inputs to optimise nutrient availability, whereas conventional systems predominantly rely on excessive chemical fertilisers, which compromise long-term sustainability through soil degradation and environmental pollution. This study provides a comprehensive review of existing literature, encompassing field experiments, long-term trials and simulation modelling to evaluate the concepts, objectives and principles of INM across diverse agroecosystems. Studies report substantial reductions in greenhouse gases (GHG) emissions (20 % to over 1300 %) under INM across India, Zimbabwe and China, highlighting its global potential. The integrated application of organic and biofertilisers increased available phosphorus by about 7.5 % over 100 % of the recommended dose of fertiliser (RDF) alone. The highest soil organic carbon (0.894 %) was recorded under 25 % RDF + 75 % poultry manure (10 t ha^{-1}), compared with 0.614 % under sole RDF, while maximum soil microbial biomass carbon was observed with 50 % inorganic N + 25 % farmyard manure combined with dual cropping of *Azolla*. Findings indicate that INM significantly improves crop yield over conventional practices while enhancing nutrient use efficiency (NUE) and farm profitability by positively influencing the physical, chemical and biological properties of soils. This review highlights that INM is a sustainable, innovative and eco-friendly strategy for managing reactive nitrogen losses, improving soil quality and ensuring global food security.

Keywords: biofertilisers; greenhouse gas emissions; integrated nutrient management; nutrient use efficiency

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Introduction

Future crop production goals

Exponential population growth, changing consumption patterns and the degradation of arable land and natural resources pose severe threats to global food security (1). Particularly in developing nations, agriculture plays a critical role in enhancing food security and poverty reduction. As a result, conventional practices rely on the intensive utilisation of agrochemicals, such as fertilisers and pesticides, to boost food production. However, these processes have been associated with soil degradation, soil nutrient imbalance, low nutrient use efficiency (NUE) and environmental pollution, which poses a significant risk to the future sustainability of agriculture (1). Hence, the adoption of climate-smart technologies such as integrated nutrient management (INM) is one way by which agricultural production may be optimised to enhance efficiency and environmental protection. Global forecasts predict that agricultural production, particularly that of cereals, must increase by nearly 70 % (approximately 43 million metric tonnes (MMT) annually) to fulfil global food demands by 2050 (2). Thus, these objectives can only be realised through the adoption of efficient and sustainable techniques, such as INM.

Environmental concerns

The increasing global population, coupled with climate variability and environmental uncertainties, has intensified the challenge of sustaining crop productivity under changing agroecosystems (3). Contemporary agricultural systems extend beyond food production and exert significant pressure on natural resources, including water, energy and land, due to competing demands such as urbanisation and industrial expansion (4). Consequently, the paradigm of agricultural development has shifted from yield maximisation towards optimising productivity in conjunction with environmental sustainability and social equity (5). Climate change

further exacerbates these challenges, as highlighted in the fourth assessment report of the intergovernmental panel on climate change (IPCC), which documented a substantial rise in global GHG emissions. Total emissions reached approximately 49.5 Gt CO_2-equivalents by 2010, exceeding historical levels with high confidence and an uncertainty of ± 10 % (6). In addition to CO_2, non-CO_2 gases such as nitrous oxide (N_2O), methane (CH_4) and fluorinated compounds play a critical role in driving climate change and are closely associated with agricultural activities (7). Agriculture is a major contributor to GHG emissions, primarily due to the excessive and inefficient use of chemical fertilisers, particularly nitrogenous fertilisers. Imbalanced fertiliser application not only reduces NUE but also accelerates environmental degradation through mechanisms such as eutrophication, soil quality decline and increased emissions of reactive nitrogen species (8). In intensive cereal-based production systems, especially in developing regions, fertiliser overuse has been identified as a key factor leading to nutrient imbalances, low input efficiency and environmental pollution (9). In this context, INM has emerged as a climate-smart agrotechnological approach that integrates chemical fertilisers with organic and biological nutrient sources to enhance NUE and minimise environmental externalities. By improving soil physical, chemical and biological properties, INM not only sustains crop productivity but also contributes to climate change mitigation through reduced GHG emissions and improved ecosystem resilience. Thus, INM represents a scientifically robust and environmentally sustainable strategy for achieving long-term soil health and agricultural sustainability.

Methodology of literature review

Review structure

This review was conducted as a structured literature review to synthesise published evidence on INM and its role in improving soil health, nutrient availability, crop productivity and climate-change mitigation. The review focused on experimental and long-term studies examining the combined use of inorganic fertilisers, organic amendments and biofertilisers in different cropping systems. The literature was also examined to understand the mechanisms through which INM influences soil properties, nutrient cycling, soil organic carbon and greenhouse gas emissions. The literature search and selection process consisted of three main stages: identification, screening and eligibility assessment. Relevant studies were identified from selected scientific databases using predefined keywords. The retrieved publications were screened according to their titles, abstracts and relevance to the objectives of the review. Full-text articles were subsequently examined before their inclusion in the final synthesis. The review was guided by the following research question: How does integrated nutrient management influence soil health, nutrient availability, crop productivity and greenhouse gas emissions compared with conventional or single-source nutrient management practices.

Search strategy: A literature search was conducted using the major scientific databases Scopus, Web of Science, ScienceDirect, PubMed and Google Scholar. Publications available up to December 2024 were considered. The search strategy used combinations of primary and related keywords with the Boolean operators “AND” and “OR”. The major search terms included “INM”, “INM and soil health”, “INM and crop productivity”, “INM and nutrient use efficiency”, “organic and inorganic fertilisers”, “biofertilisers”, “soil organic carbon”, “soil microbial biomass carbon”, “greenhouse gas emissions”, “N_2O emissions”, “soil fertility”, “soil properties”, “nutrient availability” and “climate-smart agriculture”**.** Additional searches were conducted using combinations of these terms to identify studies dealing with specific soil properties, nutrient transformations and environmental responses to INM. Research articles containing the selected terms in the titles, abstracts or keywords were considered during the initial search. Reference lists of relevant articles were also examined to identify important studies that might not have been retrieved through the database search.

Identification and screening of literature: The identification phase involved retrieving publications from the selected databases using the defined search terms. Duplicate records retrieved from more than one database were removed before screening. The titles and abstracts of the remaining publications were examined to identify studies relevant to INM, soil fertility, crop productivity and environmental sustainability. During the screening stage, studies were considered for further evaluation when they provided information on the effects of combined nutrient management involving two or more nutrient sources, particularly inorganic fertilisers, organic manures or amendments and microbial inoculants.

Inclusion and exclusion criteria: A total of 150 research articles were initially identified and screened for relevance. After removing 28 duplicate records, 122 articles were assessed based on their titles and abstracts. Of these, 20 articles were excluded because they were not directly related to INM or did not provide relevant information on soil properties, nutrient availability, crop productivity or environmental responses. The remaining 102 full-text articles were assessed for eligibility, of which 8 were excluded due to insufficient experimental information or lack of relevance to the objectives of the review. Finally, 94 research articles were included for detailed analysis and synthesis.

Findings and Discussion

The 94 selected research articles were examined for their authors, publication years, study conditions, nutrient management practices and major findings. The literature was reviewed to assess the effects of INM on soil properties, nutrient availability, crop yield and greenhouse gas emissions. The findings were compared across different cropping systems to identify the major benefits, limitations and research gaps of INM.

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Fertiliser use and integrated nutrient management strategy

There has been a gradual rise in the consumption of nitrogen fertiliser (Fig. 1) since the early 1930s, although growth remained minimal prior to the 1950s. It took 25 years for nitrogen fertiliser consumption to reach 0.21 Mt with a replication rate of 1.4 kg N ha^{-1} during 1960–61. Following the development of high-yielding varieties of rice and wheat in the mid-1960s, nitrogen fertiliser consumption increased rapidly, rising sevenfold from 0.21 Mt to 1.48 Mt between 1960–61 and 1970–71, accompanied by a proportional increase in per-hectare consumption. According to earlier reports, agricultural growth from 1960 to 2015 increased the production of 174 crops worldwide by 28 % (10). This unprecedented production growth substantially increased crop output but also intensified exploitation of soil resources, leading to land degradation. Beneficial fertiliser policies during the 1970s and 1980s further increased nitrogen consumption from 1.48 to 8.0 MMT between 1970–71 and 1990–91, while fertiliser use per hectare increased from 8.9 to 43.1 kg. Nitrogen consumption continued to increase during the 1990s at a slower rate, peaked at 11.59 MMT in 1999–2000, remained stagnant until 2004–05 and then increased to 17.3 MMT by 2011–12. Thereafter, nitrogen use either increased gradually or remained stable during 2011–12 to 2015–16 due to the rise in the price of diammonium phosphate (DAP) and other nitrogen, phosphorus and potassium (NPK) fertilisers.

Nitrogen application patterns remain highly variable across geographic regions and temporal scales. Excessive fertiliser application can induce heavy metal accumulation, contaminate soil, water and air and contribute to environmental toxicity. Although heavy metals and radionuclides are rarely present in fertiliser materials, excessive fertiliser use may create environmental problems. For example, excessive use of urea has contributed to elevated nitrate (NO_3^-) concentrations in drinking water. In the Vamsadhara River Basin of Srikakulam, Andhra Pradesh, nitrate concentrations ranged from trace amounts to 450 mg L^{-1} (11). Current nitrate pollution in Indian water bodies is largely associated with the historical overutilisation of chemical fertilisers and animal manure. Similarly, phosphatic fertilisers transported through surface runoff increase phosphate levels in water bodies, while agricultural and sewage discharges further elevate dissolved nitrogen and phosphorus concentrations. Excessive nitrogen fertiliser use also accelerates GHG emissions, reduces NUE and contributes to soil degradation through inadequate use of organic manure, crop residue retention and biological inoculation. The resulting imbalance in biological and geochemical processes reduces soil fertility, nutrient availability, fertiliser use efficiency and crop productivity. Therefore, sustainable nutrient management approaches are essential to improve fertiliser use efficiency, minimise environmental and health hazards and maintain soil fertility. Hence, INM becomes essential for restoring agroecosystem balance while preserving soil fertility and sustainability.

Dynamics of soil nutrient mineralisation and mobilisation under integrated nutrient management

Conventional practices involve the use of high doses of fertilisers at the time of planting, where 80 % of the recommended dose of fertiliser (RDF) is applied as basal fertiliser. The remaining nitrogen is applied during the initial growth stages of the crop, which is within 10 days after transplanting for rice (*Oryza sativa* L.) and within 30 days for crops like wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sorghum (*Sorghum bicholor* (L.) Moench) (12, 13). These conventional practices result in nutrient inefficiencies and losses. On the other hand, INM involves the use of inorganic fertilisers in conjunction with organic manures and biofertilisers to optimise the dynamics of nutrient cycling in soils. When farmyard manure (FYM) is added to soils alongside nitrogen fertilisers, the carbon-to-nitrogen (C : N) ratio in soils is regulated, which affects the rate of mineralisation and immobilisation. A low C : N ratio in soils leads to nitrogen availability through increased mineralisation rates (14). Organic manures and composts, particularly those enriched with nitrogen, promote nitrogen availability in soils by increasing ammonium (NH_4^+) and nitrate (NO_3^-) concentrations. Ammonification and nitrification are major biological processes responsible for nitrogen availability in soils, alongside the steady liberation of nitrogen from soil organic matter (SOM) (15, 16). Several studies demonstrate that soils amended with nitrogen-enriched composts contain more nitrogen than soils treated with chemical fertilisers alone or unfertilised controls (17, 18). The INM is an effective strategy for improving nutrient mineralisation and mobilisation, thus leading to efficient nitrogen uptake and increased soil fertility.

Concept and principles of integrated nutrient management

Concept of integrated nutrient management

The term INM involves the maintenance or enhancement of soil fertility and plant nutrient provision for crop production at an expected level, which can be realised through optimising the use of all sources of plant nutrients in an integrated, viable manner (19). In essence, INM entails the integration of diverse nutrient sources, including inorganic, organic and biological inputs, to maintain optimum levels of agricultural production, improve soil physicochemical as well as biological properties and achieve plant nutrition for sustainable agriculture (20). This management technique focuses on optimising the entire nutrient cycle-encompassing inputs and outputs of macronutrients (N, P and K) and micronutrients (e.g., Zn^{2+}, fe^{2+}, M^{2+} and Cu^{2+}) to ensure that nutrient demand and nutrient availability are synchronised (21).

The standard workflow for implementing an INM strategy involves four core stages (21):

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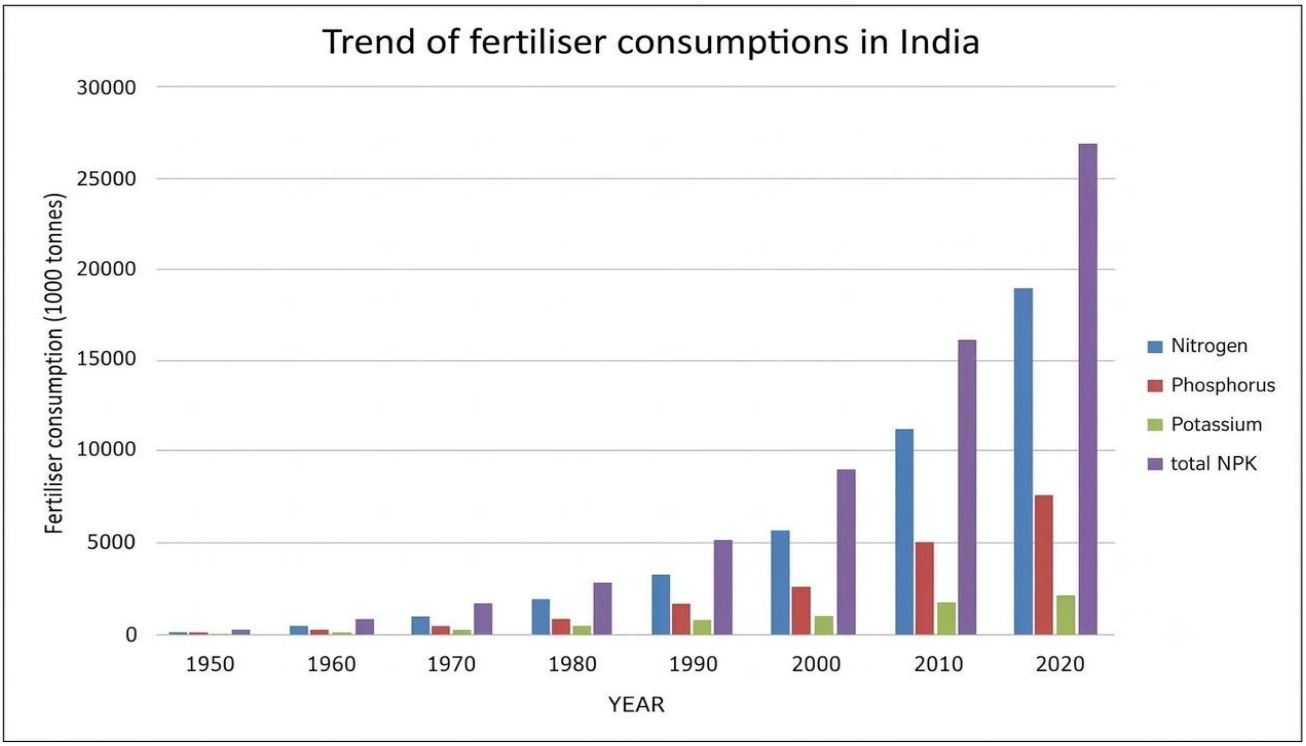


Fig.1. India's annual fertiliser consumption pattern (Fertiliser Association of India, 2021).

Total NPK fertiliser consumption in thousand tonnes and disaggregated consumption trends for nitrogen versus phosphorus/potassium inputs in thousand tonnes, illustrating post-1960s growth following the introduction of high-yielding crop varieties.

Soil nutrient diagnosis: Establish the baseline availability of soil nutrients and diagnose crop nutrient deficiencies. Soil sampling and laboratory analyses of these samples are generally used to establish the soil nutrient status. However, there are two approaches to determining nutrient deficiencies. First, visual symptoms can indicate specific nutrient deficiencies. Second, in the absence of visible symptoms, both the soil and tissue samples after harvesting should be analysed in a laboratory and compared with a reference healthy sample.

Constraint identification: Carefully monitor the constraints and opportunities for soil fertility management practices and how these relate to the nutrient diagnosis. For instance, this concerns either overuse or insufficiency.

Selection of best management practices: Choose tailored technologies and management practices providing balanced nutrients according to climate and soil class. Calculating the soil nutrient budget by comparing nutrient inputs and outputs helps to identify suitable INM components as nutrient sources.

Execution and monitoring: Carefully plan and execute field applications based on crop demand, phenological growth stages and target yield potential. Adoption relies on locally available farm nutrient resources and grower's technical capacity.

Principles of integrated nutrient management

The fundamental principle of integrated nutrient management follows three major core principles:

Maximum use of organic matter

Integrated nutrient management emphasises, maximising the application of organic matter such as compost, FYM, green manure and crop residues. The significant contribution of organic matter is that it directly provides N, P and S to the soil, it is equally important to note that organic matter is vital for improving the fertility of the soil and thereby helping to promote the productivity of the soil (22, 23).

Judicious use of synthetic fertilisers

Integrated nutrient management encourages the judicious use of synthetic fertilisers along with supplement nutrients sources such as organic manures and biofertilisers. This practice guarantees that crops obtain the nutrients required by plants at the right time and in the right amounts (24). In this way, nutrient efficiency is achieved and imbalanced use of resources is avoided. In using synthetic nutrients to supplement their natural counterparts, INM proactively seeks to build a better future. It optimises crop yields with minimal potential for adverse environmental effects such as nutrient runoff and soil degradation (25, 26).

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Minimising plant nutrient losses

One of the basic principles of INM is to minimise the loss of nutrients from the soil by adopting the right strategies that prevent nutrient leaching, volatilisation and erosion, using techniques that promote soil and water conservation such as mulching, cover cropping and contour farming, which improve the retention of nutrients in the soil profile (27). In essence, these principles of INM are designed to ensure that there is no limitation on plants' access to their basic needs during growth and development, thereby improving the nutrient use efficiency and ensuring sustainable crop yields (28). In essence, these principles of INM are designed to ensure a balanced and sustainable agricultural system that promotes and conserves soil health and crop productivity.

Impact of integrated nutrient management on agricultural greenhouse gas emissions

Greenhouse gas emissions from agricultural fields, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are increasing globally due to anthropogenic activities and play a major role in climate change by trapping atmospheric heat (Table 1) (29, 30). Agriculture contributes about 12 % of total global GHG emissions, while broader farm-related activities account for nearly 16 –27 % (31, 32). These emissions occur at all stages of agricultural production, starting from land preparation and fertiliser application to harvesting and storage (33). On average, global agriculture emits around 436 Mt of GHGs annually. However, emissions have declined by approximately 23 % since 1990, mainly due to reduced livestock populations and lower nitrogen fertiliser use (34). At the same time, global initiatives such as achieving climate neutrality by 2050 have increased the need for sustainable mitigation strategies (35). In this context, INM has emerged as an effective approach for reducing GHG emissions while maintaining productivity. Studies in India have reported significant reductions in emissions (20 % to over 1300 %) in crops such as rice, wheat and mustard under INM practices (36–38). Similar results have been observed globally, including a 17.1 % reduction in maize in Zimbabwe and significant reductions in rice–wheat systems in China (39, 40). Excessive and imbalanced use of chemical fertilisers is a major cause of increased emissions and nutrient leaching, whereas INM improves nutrient-use efficiency, reduces nitrogen losses and minimises environmental impacts (27). Additionally, INM promotes the use of organic inputs, which enhance soil health and sustainability. The integration of organic manures with practices such as crop residue incorporation and conservation tillage further helps in reducing GHG emissions, improving soil quality and enhancing carbon sequestration (28).

Impact of integrated nutrient management on available soil nitrogen, phosphorus and potassium

Integrated nutrient management integrates inorganic fertilisers, organic manures and biofertilisers to maintain a balanced nutrient supply while overcoming single-source limitations (41–43). Beyond supplying nutrients, INM stimulates soil biological dynamics, including mineralisation, immobilisation, humification and microbial transformations. Organic inputs enhance microbial activity, accelerating SOM turnover into bioavailable forms (NH_4^+, NO_3^-, $H_2PO_4^-$, K^+). During decomposition, part of the organic material is converted into stable humic substances, which improve soil's organic carbon, cation exchange capacity, aggregate stability and water-holding capacity, thereby increasing the soil's ability to retain and gradually release nutrients.

Table 1. Comparative analysis of India's greenhouse gas emissions under conventional and integrated nutrient management systems

Sl. no.	Crop	Management practice	GHGs (kg CO_2 eq. ha^{-1})	Reference
1	Maize	Conventional	110	(39)
		INM	94	
2	Wheat	Conventional	252	(39)
		INM	228	
3	Wheat	Conventional	383	(36)
		INM	268	
4	Mustard	Conventional	30016	(37)
		INM	2064	
5	Rice	Conventional	90	(38)
		INM	75	
6	Maize	Conventional	338	(39)
		INM	193	

INM: Integrated nutrient management.

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The combined application of vermicompost, FYM, chemical fertilisers, microbial inoculants and lime has consistently improved nitrogen availability and overall soil macronutrient status. Long-term fertiliser experiment (LTFE) studies in maize and wheat have shown that INM increases soil nitrogen status compared with unfertilised controls by stimulating microbial decomposition, enhancing biological nitrogen fixation and improving nutrient recycling within the soil–plant system (44). Similarly, integrating FYM, inorganic fertilisers, *Azotobacter* and phosphate-solubilising bacteria (PSB) has been reported to increase available phosphorus by approximately 7.5 % over the application of 100 % recommended fertiliser alone (45, 46). This improvement is mainly attributed to the production of organic acids and phosphatase enzymes during decomposition, which reduce phosphorus fixation and convert insoluble phosphorus into plant-available forms (47).

Integrated nutrient management also increases the availability of potassium (K^+) and sulphur (SO_4^{2-}) by accelerating residue decomposition, mineral weathering and microbial mineralisation, thereby strengthening nutrient cycling in soil. Significantly higher concentrations of available nutrients (N: 198 kg ha^{-1}, P: 14.5 kg ha^{-1} and K: 111.9 kg ha^{-1}) are sustained under INM relative to controls (48). In addition, biological nitrogen fixation by *Azotobacter*, phosphorus solubilisation by *Phosphobacter* and the gradual release of nutrients from decomposing organic matter contribute to residual soil fertility even after crop harvest (49, 50). Overall, the interaction between biological activity and soil biochemical processes under INM enhances nutrient use efficiency, reduces nutrient losses and sustains long-term soil fertility and productivity (51, 52) (Table 2).

Impact of integrated nutrient management on soil organic carbon

Integrated nutrient management plays a crucial role in enhancing SOC by combining organic amendments with inorganic fertilisers. This approach increases carbon inputs while promoting microbial processes involved in SOC formation. Significant differences in SOC were observed after crop harvest, with the highest SOC (0.894 %) recorded under RDF combined with 75 % poultry manure at 10 t ha^{-1} (63), whereas the lowest SOC (0.614 %) was obtained with the sole application of RDF. The higher SOC under INM is attributed to the continuous addition of organic residues, which stimulate microbial activity, leading to mineralisation of labile organic matter, temporary nutrient immobilisation in microbial biomass and humification into stable humic substances. These compounds are further protected within soil aggregates and through organo-mineral associations, enhancing long-term carbon stabilisation and soil fertility (64).

Similarly, the highest SOC (1.52 %) at harvest was recorded with 50 % NPK combined with *Azolla* compost at 5 t ha^{-1}, representing increases of 24.6 % and 17.0 % over the control and recommended NPK treatment, respectively (65). The integrated application of *Azolla* compost and mineral fertilisers improved microbial activity, nutrient cycling and humus formation, resulting in greater SOC accumulation. These findings showed that the integration of organic manures with inorganic fertilisers is more effective than the sole application of chemical fertilisers in improving SOC and sustaining soil quality (66) (Table 3).

Impact of integrated nutrient management on soil microbial biomass carbon

Soil microbial biomass carbon (SMBC) is a sensitive indicator of soil biological activity and responds markedly to INM practices involving the combined use of organic and inorganic nutrient sources. Significant variations in SMBC have been observed under different nutrient management strategies, including farmyard manure (FYM; 25 % RDN), inorganic fertilisers (50 %) and the incorporation of *Azolla* in rice cultivation (69). The highest SMBC was recorded under the integrated application of 50 % nitrogen through chemical fertilisers, 25 % nitrogen through FYM and dual cropping with *Azolla*. This improvement can be attributed to the continuous supply of readily decomposable organic substrates that provide carbon and energy for soil microorganisms. During decomposition, organic residues undergo mineralisation, releasing plant-available nutrients, while a portion of these nutrients is temporarily retained in microbial biomass through immobilisation, thereby reducing nutrient losses and maintaining a steady nutrient supply.

As microbial biomass turns over, microbial metabolites and plant residues are transformed through humification into stable soil organic matter, which contributes to long-term carbon sequestration and enhances soil structural stability. The accumulation of humified organic matter promotes the formation of stable soil aggregates, improves pore continuity, water retention and aeration and creates a favourable habitat for microbial communities. In addition, *Azolla* contributes biologically fixed nitrogen and fresh organic biomass, further stimulating microbial activity and accelerating nutrient cycling. These interconnected biological and biochemical processes strengthen soil formation and improve soil quality by enhancing the development of stable organo-mineral complexes and increasing the soil organic carbon pool. Similar improvements in SMBC under balanced fertilisation integrated with organic amendments, such as vermicompost, green manure, *Azolla* and *blue-green algae* (BGA), have also been reported (70) (Table 4). These findings demonstrate that INM not only increases microbial biomass but also promotes efficient nutrient cycling and long-term soil fertility through enhanced mineralisation, immobilisation, humification and soil carbon stabilisation.

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Table 2. Comparative variability of available soil sodium, phosphorus and potassium under conventional and integrated nutrient management systems in India

Sl. no.	Crop	Management practice	N (Kg ha^{-1})	P (Kg ha^{-1})	K (Kg ha^{-1})	Reference
1	Rice	Conventional	74.9(mg kg^{-1})	31.85	162	(53)
		INM	72.4(mg kg^{-1})	34.3	166.5	
2	Green gram	Conventional	320.65	31.58	190.86	(54)
		INM	333.23	34.58	205.83	
3	Maize-Mustard	Conventional	284.30	10.91	127.83	(55)
		INM	501.82	32.85	243.62	
4	Maize	Conventional	385.22	9.39	-	(56)
		INM	565.45	14.97	-	
5	Rice	Conventional	216.08	24.16	-	(57)
		INM	229.47	25.84		
6	Sorghum- wheat	Conventional	280	30.96	388	(58)
		INM	313	37.08	460	
7	Maize	Conventional	206	90.5	171	(59)
		INM	300	96.6	180	
8	Rice-mustard-sesame	Conventional	208.4	36.7	145.6	(60)
		INM	248.5	49.9	156.6	
9	Rice-rice	Conventional	219.0	12.0	100.3	(61)
		INM	223.7	19.6	110.0	
10	Rice	Conventional	201.50	41.93	236.11	(62)
		INM	220.36	44.38	242.85	

INM: Integrated nutrient management; N: sodium; P: phosphorus; K: potassium.

Table 3. Comparative variability of soil organic carbon under conventional and integrated nutrient management systems in India

Sl. no.	Crop	Management practice	O.C	Reference
1	Rice-rice	Conventional	4.50 (g kg^{-1})	(61)
		INM	5.85 (g kg^{-1})	
2	Green gram	Conventional	0.67(%)	(65)
		INM	0.75(%)	
3	Rice-brown sarson	Conventional	1.54 (g kg^{-1})	(67)
		INM	1.76 (g kg^{-1})	
4	Rice	Conventional	5.58 (g kg^{-1})	(62)
		INM	5.69 (g kg^{-1})	
5	Maize-mustard	Conventional	1.80 %	(55)
		INM	2.63 %	
6	Maize	Conventional	0.66 %	(56)
		INM	1.54 %	
7	Groundnut	Conventional	3.9 (g C kg^{-1})	(59)
		INM	6.4 (g C kg^{-1})	
8	finger millet	Conventional	4.3 (g C kg^{-1})	(68)
		INM	4.6 (g C kg^{-1})	
9	Maize-chickpea	Conventional	6.5 (g C kg^{-1})	(68)
		INM	8.1 (g C kg^{-1})	
10	Rice	Conventional	0.38 %	(57)
		INM	0.41 %	
11	Sorghum- wheat	Conventional	5.11 (g kg^{-1})	(58)
		INM	6.77 (g kg^{-1})	

INM: Integrated nutrient management; O.C: organic carbon.

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Table 4. Comparative variability of soil microbial biomass carbon under conventional and integrated nutrient management systems in India

Sl. no.	Crop	Practice	SMBC	Reference
1	Rice- brown sarson	Conventional	226.5 (mg g^{-1})	(67)
		INM	230 (mg g^{-1})	
2	-	Conventional	209.97 (mg kg^{-1})	(71)
		INM	250.56 (mg kg^{-1})	
3	Sorghum- wheat	Conventional	214 (mg kg^{-1})	(58)
		INM	222 (mg kg^{-1})	
4	Okra	Conventional	180.02 (µg g^{-1})	(72)
		INM	244.86 (µg g^{-1})	
5	Rice	Conventional	315.9(mg kg^{-1})	(69)
		INM	366.2 (mg kg^{-1})	
6	Sorghum –wheat	Conventional	169.4 (mg kg^{-1})	(73)
		INM	278.9(mg kg^{-1})	
7	Rice-wheat	Conventional	307.6(µg $g^{-1)}$	(74)
		INM	407.5(µg $g^{-1)}$	
8	Cotton + green gram	Conventional	148.85(µg $g^{-1)}$	(75)
		INM	173.17 (µg $g^{-1)}$	

INM: Integrated nutrient management; SMBC: soil microbial biomass carbon.

Impact of integrated nutrient management on bulk density and water holding capacity in soils

The use of only inorganic fertilisers cannot support the continuous production of crops and healthy soils in situations where nutrient availability is low and the nutrient recycling rate is not at the optimum level to fulfil crop nutrient requirements. Moreover, neither organic amendments nor chemical fertilisers applied exclusively can sustain optimal yields and sustainability. The use of organic fertilisers increases physical properties such as soil structure and water-holding capacity. Extensive root development leads to increased microbial activity in the soil and decreased soil bulk density through the provision of organic matter and pore space upon decomposition (76). Integrated methods have been emphasised in which a combination of lime, farmyard manure and biofertilisers result in improved physical properties of soil and soil quality (55). Non-significant impacts of different fertility levels, FYM and biofertiliser application on the physical characteristics of soil have been noted (77). However, there is evidence that FYM applied in an amount of 5 t ha^{-1} reduces bulk density as it adds to organic matter content and soil aggregation whereas biofertilisers help in soil aggregation due to the secretion of polysaccharides acting as binding agents (77). Moreover, INM practices have proven effective in increasing the WHC because of higher organic matter and humus content due to mineralisation, solubilisation processes, as well as increased production of substances promoting plant growth, generation of antibiotics and enhanced decomposition of organic matter (78, 79). Long-term studies using chemical fertilisers alone and their combinations with organic manures showed an increase in WHC over control treatments (80). Such improvement was attributed to good root development and greater residue additions. Moreover, repeated applications of organic manures led to higher WHC owing to the formation of good soil aggregates (81) (Table 5, 6). Ample evidence indicates that nutrient management systems are vital for improving soil physical properties including soil bulk density and water holding capacity.

Impact of integrated nutrient management on grain yield, soil health and crop quality

Integrated nutrient management optimises overall soil quality and crop yields by harmonising mineral fertiliser inputs with organic manures and bioinoculants. This integrated approach enhances nutrient use efficiency, increases soil organic carbon, stimulates soil microbial activity and improves soil physical properties such as bulk density, aggregation, porosity and water-holding capacity. Organic inputs serve as substrates for microbial growth, accelerating nutrient mineralisation and humification, while beneficial microorganisms facilitate nutrient solubilisation, biological nitrogen fixation, phytohormone production and suppression of soil-borne pathogens. These processes improve nutrient availability, promote root development and sustain crop productivity while reducing dependence on synthetic fertilisers and minimising nutrient losses and associated environmental impacts (21).

The improvement in soil biological, chemical and physical properties under INM contributes to higher crop produce quality through enhanced nutrient uptake, improved photosynthetic efficiency and better accumulation of proteins, carbohydrates, vitamins and other quality attributes.

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Table 5. Comparative variability of bulk density and water holding capacity under conventional and INM systems in India

Sl. No.	Crop	Practice	Bulk density (Mg m^{-3})	WHC (%)	Reference
1	Maize	Conventional	1.44	14.02	(82)
		INM	1.41	17.14	
2	Maize-mustard	Conventional	1.45	-	(55)
		INM	1.29	-	
3	Maize–wheat	Conventional	1.53	-	(83)
		INM	1.49	-	
4	Rice-wheat	Conventional	1.37	37.7	(84)
		INM	1.33	40.2	
5	Maize	Conventional	1.75	24	(85)
		INM	1.41	35	
6	Pearl Millet-mustard	Conventional	1.37	-	(86)
		INM	1.10	-	
7	Sorghum-wheat	Conventional	1.30	-	(87)
		INM	1.20	-	
8	Groundnut	Conventional	1.43	27.00	(88)
		INM	1.38	38.17	

INM: Integrated nutrient management; WHC: water holding capacity.

Table 6. Comparative variability of grain yield under conventional and INM Systems in India

Sl. No.	Crop	Practice	Rice equivalent yield	References
1	Rice	Conventional	5113 kg ha^{-1}	(89)
		INM	5459 kg ha^{-1}	
2	Rice	Conventional	4.02 t ha^{-1}	(90)
		INM	4.18 t ha^{-1}	
3	Rice	Conventional	4132 kg ha^{-1}	(91)
		INM	6690 kg ha^{-1}	
4	Rice	Conventional	4.43 t ha^{-1}	(92)
		INM	4.38 t ha^{-1}	
5	Rice	Conventional	3.99 t ha^{-1}	(93)
		INM	6.04 t ha^{-1}	
6	Rice-niger	Conventional	3.1 t ha^{-1}	(94)
		INM	4.1 t ha^{-1}	
7	Rice-rice	Conventional	6.00 t ha^{-1}	(95)
		INM	6.50 t ha^{-1}	
8	Rice–rice	Conventional	8.40 t ha^{-1}	(96)
		INM	9.47 t ha^{-1}	
9	Rice-wheat	Conventional	34.62 q h^{-1}	(97)
		INM	36.62 q h^{-1}	
10	Rice-wheat	Conventional	55.5 q h^{-1}	(97)
		INM	61.3 q h^{-1}	

INM: Integrated nutrient management.

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Increased soil organic matter also strengthens soil resilience by improving nutrient buffering capacity and maintaining favourable conditions for long-term soil fertility.

The long-term sustainability of INM depends not only on its agronomic and ecological benefits but also on its economic feasibility and adoption at the farm level. By improving nutrient use efficiency and reducing nutrient losses, INM enhances input-use efficiency and contributes to stable crop productivity, thereby increasing long-term farm profitability.

However, its large-scale adoption remains constrained by the limited availability of organic amendments and good quality biofertilisers, high labour requirements for the collection and application of organic inputs, greater initial investment and inadequate technical knowledge and extension support. Addressing these constraints through improved access to organic resources, strengthened extension services and the development of site-specific nutrient management strategies will be essential for the widespread adoption and long-term sustainability of INM-based production systems.

Conclusion

This review highlights the role of integrated nutrient management (INM), through the combined application of organic amendments, mineral fertilisers and biofertilisers, in sustaining soil health by regulating soil physical, chemical and biological dynamics. Organic inputs increase SOM and stimulate microbial mineralisation, immobilisation and humification, while mineral fertilisers supply immediate, synchronised crop nutrient demands. Beneficial microbes promote biological nitrogen fixation, nutrient solubilisation and phytohormone production, increasing overall nutrient uptake efficiency. Consequently, INM serves as an effective agroecological strategy for sustaining long-term soil fertility, crop productivity and environmental quality. Future research should focus on clarifying microbial-biochemical transformation mechanisms, designing site-specific climate-resilient nutrient regimes, quantifying long-term soil carbon sequestration dynamics and integrating precision farming technologies. Integrated nutrient management also enhances crop productivity and helps reduce greenhouse gas emissions. Therefore, it is a sustainable approach for long-term agricultural productivity and environmental protection.

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Authors' contributions

RS conceived the review, carried out the literature search, organised the relevant literature and drafted the manuscript. NK contributed to the literature search and organisation and interpretation of the information. JKT contributed to the literature review and manuscript preparation. RKK assisted in the collection of relevant literature and revision of the manuscript. ASS contributed to literature compilation and critical reading of the manuscript. AS assisted with reference management, literature compilation and manuscript editing. DK and AR provided scientific guidance, critically reviewed the manuscript and contributed to its final revision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely to assist with language editing and grammar correction. The authors critically reviewed and edited the content and take full responsibility for the final content of the manuscript.

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