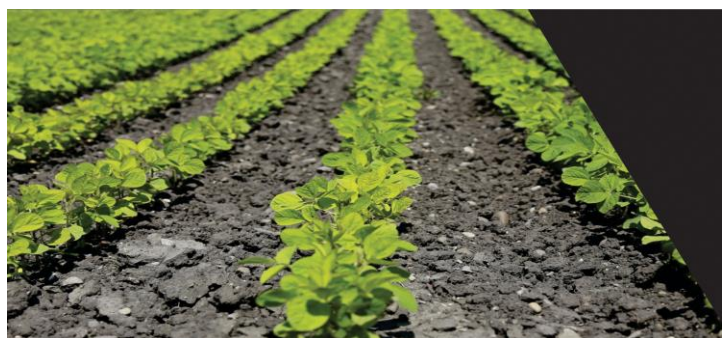




International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(8): 179-190
Received: 08-05-2026
Accepted: 12-06-2026

Adarsh Pandey
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Shakti Om Pathak
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Karmnath Kumar
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Atul Bhatti
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Yuvraj Sajwal
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Vaishnavendra Kumar
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Debabrata Dhar
Department of Natural Resource
Management, Faculty of Agricultural
Sciences (FASC), SGT University,
Gurugram, Haryana, India

Rameshwar Pandey
Division of Agronomy, ICAR-Indian
Agricultural Research Institute (ICAR-
IARI), New Delhi, Delhi, India

Corresponding Author:
Rameshwar Pandey
Division of Agronomy, ICAR-Indian
Agricultural Research Institute (ICAR-
IARI), New Delhi, Delhi, India

Advanced Integrated Nutrient Management Practices for Millet Cultivation Improve Crop Growth, Yield and Quality

Adarsh Pandey, Shakti Om Pathak, Karmnath Kumar, Atul Bhatti, Yuvraj Sajwal, Vaishnavendra Kumar, Debabrata Dhar and Rameshwar Pandey

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i8c.6221>

Abstract

The durability and high nutritional content of millets, such as pearl millet, foxtail millet, finger millet, proso millet, barnyard millet and kodo millet, make them essential for food security in semi-arid and drought-prone areas. A sustainable farming method called Integrated Nutrient Management (INM) blends biological, inorganic and organic fertilizers to enhance crop quality, production and soil health. The improvements in INM techniques for millet crops are examined in this study with an emphasis on how they affect grain quality, production and growth. INM techniques have enhanced nitrogen absorption, decreased use of artificial fertilizers and raised millet yield. Higher yields without sacrificing environmental sustainability have been achieved by using legume-based rotations and intercropping with millets, which have also enhanced nitrogen fixation and soil nutrient cycling. The amount of grain produced, its nutritional profile and its size and homogeneity are all improved by the synergy between organic and artificial nutrients. These factors are crucial for marketability and customer acceptability.

Keywords: Integrated Nutrient Management (INM), millets, crop growth, yield and quality, sustainable agriculture and organic-inorganic fertilizer integration

1. Introduction

Millets are among the oldest cultivated cereal crops and are increasingly recognized as climate-resilient grains capable of ensuring food, nutritional, and livelihood security under changing environmental conditions (Kumar *et al.*, 2023; FAO, 2023) ^[21, 1]. They are regarded as climate-smart crops because of their high nutritional content, resistance to heat and drought, and capacity to prevent soil erosion on marginal soils. Their ability to grow under diverse ecological conditions while utilizing atmospheric CO₂ efficiently makes them suitable for a wide range of farming systems (Maitra *et al.*, 2024; Banerjee *et al.*, 2020; Brahmachari *et al.*, 2018) ^[2, 3, 4]. Millets are referred to as "miracle crops" because of their many health advantages and ability to survive under harsh weather conditions (Banerjee and Maitra, 2020) ^[3]. They are highly nutritious, containing dietary fiber, vitamins, minerals, resistant starch, protein, amino acids, and fatty acids, making them valuable for combating chronic diseases, improving satiety, and ensuring prolonged glucose release (Anitha *et al.*, 2020; Zhang *et al.*, 2023) ^[11, 5]. Despite these advantages, millet productivity remains below its genetic potential because of declining soil fertility, nutrient mining, low soil organic matter, imbalanced fertilizer use, and poor nutrient-use efficiency. These constraints are further intensified by climate change, erratic rainfall, and drought, necessitating sustainable nutrient management strategies to improve crop productivity and soil health (Louhar *et al.*, 2021; Warisa *et al.*, 2025; Hasanath *et al.*, 2026) ^[22, 6, 7]. Global hunger and the need to feed the rapidly growing population remain major challenges, driven by nutrient deficiencies, declining food production, resource limitations, and geopolitical conflicts that disrupt food systems (Nithiyanantham *et al.*, 2019) ^[8]. It has been projected that global food production must increase by nearly 70% by 2050 to meet future food demands (Jat *et al.*, 2015) ^[9]. Millets continue to gain global recognition because of their importance in sustainable agriculture and food security. According to FAO estimates, global millet production reached approximately 28.33 million metric

tons in 2019 and 30.08 million metric tons in 2021. India contributes nearly 41% of global millet production, followed by Niger (12%) and China (8%). Recognizing their nutritional significance, the Government of India declared 2018 as the "National Year of Millets" and promoted millets under the National Nutrition Mission (Poshan Abhiyan). Subsequently, India's proposal to declare 2023 as the International Year of Millets (IYoM-2023) was endorsed by 72 countries and adopted by the United Nations General Assembly on 5 March 2021 (Harish *et al.*, 2024) ^[12]. Sustainable intensification of millet production requires efficient nutrient management. Excessive dependence on chemical fertilizers has contributed to soil degradation, nutrient imbalance, and deterioration of soil biological activity. Integrated Nutrient Management (INM) combines organic manures, inorganic fertilizers, and biofertilizers to achieve balanced nutrient supply while maintaining soil fertility and productivity. Organic manures such as farmyard manure, pig manure, and sheep manure improve soil structure, aeration, infiltration, porosity, water-holding capacity, and soil organic carbon (Madhurya *et al.*, 2022) ^[13]. Vermicompost enhances nutrient availability and mobilization, whereas micronutrients such as zinc and sulfur, together with biofertilizers, play vital roles in improving plant growth and nutrient-use efficiency (Das and Biswas, 2022) ^[14]. Furthermore, recent advances involving plant growth-promoting rhizobacteria (PGPR), nano-fertilizers, microbial inoculants, and precision nutrient management have further strengthened climate-smart INM by improving nutrient-use efficiency, crop productivity, soil fertility, and environmental sustainability (Basu *et al.*, 2021; Raliya *et al.*, 2018; Dimkpa & Bindraban, 2018; Bhardwaj *et al.*, 2014) ^[15, 89, 85, 16]. Although Integrated Nutrient Management research has advanced, studies in millets remain fragmented. Limited emphasis has been placed on integrated approaches combining organic, inorganic, biological inputs, biochar, microbial consortia, and precision nutrient management. Comprehensive evaluation of their effects on productivity, soil health, grain quality, and sustainability remains inadequate. Therefore, this review critically synthesizes recent advances in advanced INM practices for millet cultivation, identifies existing research, and highlights future research priorities for developing sustainable, resilient, and high-productivity millet production systems.

2. Literature Search Methodology

This review was conducted using a structured narrative literature review approach to comprehensively evaluate recent advances in Integrated Nutrient Management (INM) for millet cultivation. Relevant scientific literature published between 2018 and 2026, with greater emphasis on studies from 2020–2026, was systematically retrieved from internationally recognized databases, including Google Scholar, Scopus, Web of Science, Science Direct, Springer Link, Wiley Online Library, Taylor &

Francis Online, CAB Abstracts, and the Food and Agriculture Organization (FAO) database. The literature search employed Boolean operators (AND, OR) using keywords such as "Integrated Nutrient Management," "Millets," "Pearl Millet," "Finger Millet," "Foxtail Millet," "Organic Manures," "Biofertilizers," "Nano-fertilizers," "Plant Growth-Promoting Rhizobacteria (PGPR)," "Arbuscular Mycorrhizal Fungi (AMF)," "Soil Health," "Nutrient Use Efficiency," "Crop Productivity," "Precision Nutrient Management," and "Climate-Smart Agriculture." Peer-reviewed research articles, review papers, book chapters, conference proceedings, and technical reports directly related to nutrient management in millet production systems were included, whereas duplicate records, non-peer-reviewed publications, non-English articles, and studies outside the scope of this review were excluded. The selected literature was critically analyzed and thematically synthesized to examine the evolution of INM, its major components, effects on soil health, crop growth, nutrient uptake, yield, grain quality, environmental sustainability, current challenges, and future research priorities for sustainable millet production.

3. Importance of millets in sustainable agriculture

Millets have emerged as key crops for sustainable agriculture due to their resilience to climate variability, low input requirements, and exceptional nutritional value. These crops thrive under drought, high temperatures, and poor soil fertility, making them highly suitable for rainfed and marginal production environments. Compared with major cereals, millets require less water, fertilizers, and pesticides, thereby reducing production costs and minimizing environmental impacts. Their extensive root systems improve soil structure, enhance soil organic carbon, reduce erosion, and support beneficial soil microorganisms, contributing to long-term soil health and ecosystem sustainability (Raj *et al.*, 2024) ^[17]. In addition, millets are rich in dietary fiber, protein, essential minerals, vitamins, and bioactive compounds, making them valuable for addressing malnutrition and improving human health (Jacob *et al.*, 2024) ^[18]. As noted by Ghosh *et al.* (2024) ^[19], millets have the potential to become the staple of our plate, reflecting their growing importance in future food systems. Furthermore, millet cultivation contributes directly to food security, climate resilience, biodiversity conservation, and several United Nations Sustainable Development Goals, highlighting their pivotal role in building sustainable and resilient agricultural systems (Mehta *et al.*, 2024; Kumar *et al.*, 2025) ^[20, 21].

4. Millet production systems: An overview

According to Louhar *et al.*, (2020) ^[22], the major millets cultivated in India have diverse origins, with pearl millet and sorghum originating in Africa, and others like little millet and Kodo millet being native to India. Their cultivation is widespread, with prominent growing states including Rajasthan, Maharashtra and Karnataka.

Table 1: Crop (Scientific names), place of origin and major growing states in India.

Sr. No.	Crop (Scientific names)	Major growing states in India
I.	Pearl millet <i>Cenchrus americanus</i> (L.)	Rajasthan, Maharashtra, Uttar Pradesh, Haryana and Gujarat
II.	Sorghum (<i>Sorghum bicolor</i>)	Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Gujarat, Rajasthan, Uttar Pradesh and Tamil Nadu
III.	Proso or common millet/Cheena (<i>Panicum miliaceum</i>)	Bihar, Northeast India, and Maharashtra
IV.	Foxtail/Italian millet/Kauni (<i>Setaria italica</i>)	Karnataka, Rajasthan, Madhya Pradesh and Chhattisgarh
V.	Ragi/finger millet (<i>Eleusine coracana</i>)	Madhya Pradesh, Maharashtra, Odisha, Uttarakhand, Uttar Pradesh and Tamil Nadu
VI.	Little millet/kutki (<i>Panicum sumatrense</i>)	Karnataka, Madhya Pradesh, Andhra Pradesh, Tamil Nadu, Jharkhand, Odisha, Maharashtra and Chhattisgarh
VII.	Kodo millet (<i>Paspalum scrobiculatum</i>)	Maharashtra, Tamil Nadu and Chhattisgarh
VIII.	Indian barnyard millet/ Sawan (<i>Echinochloa frumentacea</i>)	Karnataka, Madhya Pradesh, Uttarakhand, Uttar Pradesh and North-east India

5. Concept and evolution of integrated nutrient management (INM)

Integrated Nutrient Management (INM) is a holistic approach designed to supply crops with a balanced combination of organic, inorganic, and biological nutrient sources to sustain productivity while improving soil health (Paramesh *et al.*, 2023) [23]. The concept developed in response to the drawbacks of Green Revolution practices, where excessive reliance on chemical fertilizers led to soil nutrient imbalances, declining organic matter, and reduced fertilizer-use efficiency (Madhurya *et al.*, 2022) [13]. Historically, farmers depended on natural nutrient cycles through manures, crop residues, and legume rotations, but rising food demand shifted agriculture toward input-intensive

systems (Paramesh *et al.*, 2023) [23]. INM re-established equilibrium by integrating fertilizers with compost, biofertilizers, green manures, and recycling of farm wastes. In recent years, the approach has evolved with soil-test-based recommendations, microbial consortia, nano-fertilizers, GIS-based nutrient mapping and precision nutrient tools (Madhurya *et al.*, 2022) [13]. Today, INM is recognized as a climate-smart strategy that enhances nutrient cycling, strengthens soil biology, increases nutrient-use efficiency and ensures sustainable crop production, including in millet-based systems (Warisa *et al.*, 2025) [6].

5.1 Components of advanced INM practices in millets

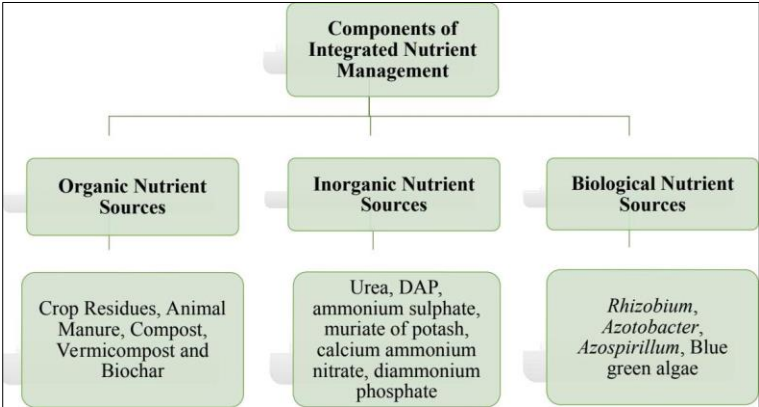


Fig 1: Components of Integrated Nutrient Management

5.1.1 Organic nutrient sources: Chemical fertilizers have significantly contaminated the air, water and soil during agricultural cultivation, which has made consumers doubt the safety and purity of food. To improve soil quality, replenish nutrients and restore soil health and fertility, organic farming is

encouraged. This approach often involves a return to traditional practices, such as the use of animal dung and crop residues, which are classified as organic manures. According to Panta and Parajulee (2021) [24], organic manures can be systematically classified into several categories.

Organic Manure	Bulky Organic Manures	FYM	(a) Cattle manure, (b) Sheep manure, (c) Poultry manure
		Compost	(a) Village/rural compost from farm wastes (b) Town/urban compost from town refuses
		Sewage and sludge	
	Concentrated Organic Manures	Oil cakes	(a) Edible oil cakes (i) Mustard cake, (ii) Groundnut cake, (iii) Sesame cake, (iv) Linseed cake (b) Nonedible Oil (i) Castor cake, (ii) Neem cake, (iii) Sunflower cake
		Slaughter house wastes	(i) Blood meal, (ii) Bone meal
		Fish meal	
		Leguminous plant	example: sun hemp, sesbania sp., mung bean, cowpea, berseem
	Green Manures	Non-leguminous plant	example: pearl millet, maize, sunflower
		Green leaf manures	example: neem, Pungamia, Gliricidia, etc.

Fig 2: Classification of Organic Manure

i) **Crop Residues and Green Manures:** Crop residues, the non-photosynthetic plant parts left in the field after harvesting, are one of the most valuable yet often

underutilized organic resources in agriculture. When retained on the soil surface, these residues improve soil structure, enhance organic matter content, reduce evaporation losses,

and contribute to long-term carbon sequestration (Guo *et al.*, 2019) ^[25]. Their presence also acts as a natural barrier against soil erosion, making it essential for soil conservation in dryland farming. Beyond these agronomic benefits, crop residues can serve as a renewable raw material for biofuel production, offering an additional economic avenue for farmers. However, modern residue management practices such as open field burning and landfill disposal continue to cause serious environmental concerns by increasing CO₂ emissions and particulate pollution (Puig *et al.*, 2019) ^[26]. Incorporating residues into soil, particularly through green manuring, provides an ecologically sound alternative. Green manure crops, most commonly legumes, fix atmospheric nitrogen and enrich the soil with both macro- and micronutrients, reducing the reliance on synthetic fertilizers. These crops also enhance soil biological activity and improve soil physical properties (Guo *et al.*, 2019) ^[25]. Certain green manures act as natural bio fumigants, suppressing weeds, nematodes, and soil-borne pathogens without compromising crop productivity. Thus, crop residues and green manures form an integral component of sustainable nutrient management, supporting both soil fertility and ecological balance (Guo *et al.*, 2019) ^[25].

ii) **Animal Manure:** Animal manures are among the oldest and most reliable nutrient sources used in agriculture, and they continue to play a central role in organic nutrient management, especially in developing countries where livestock numbers are increasing. These manures enrich the soil with essential nutrients while improving soil structure, porosity, and moisture-holding capacity (Zhou *et al.*, 2022) ^[90]. Their application to croplands helps reduce dependence on chemical nitrogen fertilizers and supports long-term soil fertility. Different types of manure, including cattle, sheep, pig, and poultry manures, vary in nutrient composition and availability, and their use is influenced by factors such as farming system, accessibility, cost, and management practices (Guo *et al.*, 2019) ^[25]. Poultry manure, for instance, is nutrient-dense and fits well within most fertilizer strategies, while cattle dung enhances soil organic carbon and contributes to stable humus formation. Bird guano is another rich organic fertilizer, valued for its high concentrations of nitrate, ammonia, proteins, and uric acid (Zhou *et al.*, 2022) ^[90]. Sheep manure has shown special promise in soils contaminated by mining activities, where it helps immobilize heavy metals and improves soil biological activity, water-use efficiency, and crop performance. Pig manure, high in both organic and inorganic nutrients, has been associated with enhanced denitrification in paddy soils, and long-term application can create conditions conducive to efficient nitrogen cycling (Guo *et al.*, 2019) ^[25]. Inconsistent nutrient composition, risks of heavy metal accumulation (particularly in cattle manure), and potential microbial contamination require careful and responsible management. When used judiciously, animal manures significantly enhance soil fertility, microbial diversity, and crop yields (Zhou *et al.*, 2022) ^[90].

iii) **Compost:** Composting is an important eco-friendly method for recycling organic waste into stable, nutrient-rich humus. Through bio-oxidative decomposition, composting reduces bulk volume, decreases moisture content, eliminates weed seeds and pathogens, and produces well-stabilized organic material suitable for agricultural use (Madhurya *et al.*, 2022) ^[13]. High-quality compost improves soil structure, increases

nutrient availability, and supports soil microbial activity. However, the effectiveness of compost depends on the quality of input materials. Poorly selected ingredients can elevate heavy metal levels, increase electrical conductivity, or slow decomposition (Zhou *et al.*, 2022) ^[90]. Recent advancements show that microbial inoculants, physical amendments, and chemical additives can improve composting efficiency and reduce greenhouse gas emissions (Madhurya *et al.*, 2022) ^[13].

- iv) **Vermicompost:** Vermicomposting uses specially selected earthworm species, primarily epigenic worms, to accelerate the decomposition of organic residues. The resulting vermicompost is rich in humic substances, nitrogen, phosphorus, and beneficial microorganisms (Madhurya *et al.*, 2022) ^[13]. Known for its superior stability and maturity, Vermicompost enhances root development, promotes nutrient uptake, and improves soil biological activity. Additionally, vermicomposting has been shown to reduce antibiotic-resistant genes (ARGs) and human pathogenic bacteria in organic waste, contributing to safer and more sustainable waste recycling (Singh *et al.*, 2023) ^[27].
- v) **Biochar:** Biochar, produced from the thermal decomposition of biomass under oxygen-limited conditions, is an emerging organic amendment with multiple agronomic and environmental benefits. It improves soil fertility, enhances crop productivity, increases water retention, and helps plants tolerate abiotic stresses (Singh *et al.*, 2023) ^[27]. Biochar is particularly effective at binding heavy metals, pesticides, and persistent organic pollutants, thereby reducing their mobility and toxicity. It also retains nitrogenous compounds such as NH₃, NH₄⁺, and NO₃⁻, minimizing nitrogen losses through leaching or volatilization (Madhurya *et al.*, 2022) ^[13]. Transforming animal manures especially pig manure into biochar significantly lowers ARG contamination and enhances soil safety. As a long-lived carbon sink, biochar further contributes to climate change mitigation through carbon sequestration (Zhou *et al.*, 2022) ^[90].

5.1.2 Inorganic nutrient sources

Applying fertilizer to soils or plant tissues is a synthetic method of supplying necessary nutrients for plant development or addressing nutritional shortages. It must include at least 5% of each of the three major nutrients (N, P, and K) and can be artificial (Hazarika *et al.*, 2023) ^[28]. They fall into three basic categories: Macronutrients such as nitrogen (absorbed as NO₃⁻ or NH₄⁺) support rapid vegetative growth through enhanced chlorophyll and protein synthesis, while phosphorus (H₂PO₄⁻, HPO₄²⁻) promotes early root development, flowering and seed formation. Potassium (K) strengthens stalks, improves drought and disease resistance and enhances grain quality. Secondary nutrients including calcium (Ca²⁺), magnesium (Mg²⁺) and sulfur (SO₄²⁻) contribute to root formation, chlorophyll development, nutrient regulation and amino acid synthesis. Equally important are micronutrients such as zinc (Zn²⁺), copper (Cu²⁺), iron (Fe²⁺ / Fe³⁺), manganese (Mn²⁺), boron (various borate forms), molybdenum (MoO₄²⁻), cobalt (Co²⁺) and nickel (Ni², Ni³), all of which play specialized roles in enzyme activation, nitrogen fixation, pollen germination, oxidation–reduction processes and grain filling. Silicon (Si (OH)₄), though not classified as essential for all crops, strengthens cell walls and enhances plant vigor, stress tolerance and productivity. Together, these nutrients form an integrated system that supports optimal plant growth and resilience (Jote, 2023) ^[29].

5.1.3 Biological nutrient sources

Applications of biofertilizers to soil, seeds, or surfaces result in the infiltration of plant tissues by live microorganisms that promote growth. These microbes, which are usually bacteria or fungi, can fix nitrogen, solubilize phosphate, oxidize sulfur, create hormones for plants, and break down organic materials. Plantgrowth-promoting rhizobacteria (PGPR) are the most widely utilized type of biofertilizer (Madhurya *et al.*, 2022) ^[13]. They boost plant development and lessen plant susceptibility to illnesses brought on by plant pathogens. Increased shoot and root weights, delayed senescence, chlorophyll content, nutrient absorption, protein content, hydraulic activity, root development, yield, leaf area, and resistance to abiotic stress are among the advantages. Biofertilizers that fix nitrogen, such as *Rhizobium*, *Azotobacter*, *Azospirillum*, and blue-green algae, and those that dissolve phosphorus, such as *Pseudomonas striata*, *Bacillus polymixa*, *Aspergillus awamori*, and *Penicillium digitatum*, are commonly used (Panta and Parajulee, 2021) ^[24].

6. Cropping systems for sustainable millet production

6.1 Fundamentals of the cropping system

- Choose crops that enhance one another.
- Make effective use of the resources that are available.
- Restore, preserve, and improve the fertility of the soil.
- Select a variety of development cycles.
- Select a variety of crop species.
- Cover the soil.
- Plan your cropping strategy strategically and adjust it as necessary.

Rainfall, soil type, soil moisture content, and length of growing period all affect cropping methods (Table - 2). While soil retains moisture, rainfall affects crop performance. Millets tolerate 350 mm of rainfall, but maize needs 500–600 mm and sorghum 400 mm (Sukanya *et al.*, 2024) ^[30].

Table 2: Factors Affecting Cropping Methods

Rainfall (mm)	Soil type	Soil moisture content (mm)	LGP (weeks)	Cropping system
350-625	Alfisol and shallow vertisol	100	20	Single crop (Kharif)
	Deep aridsols, entisols			Single crop (Kharif or Rabi)
	Deep entisols			Single crop (Rabi)
650-750	Alfisol, entisol, vertisol	100	20-30	Intercropping
750-900	Deep alfisols, deep vertisols, entisols, inceptisols	150	30	Double cropping with monitoring
>900		200	>30	Sequential and double cropping assured

6.2 Important factors influencing cropping pattern in India

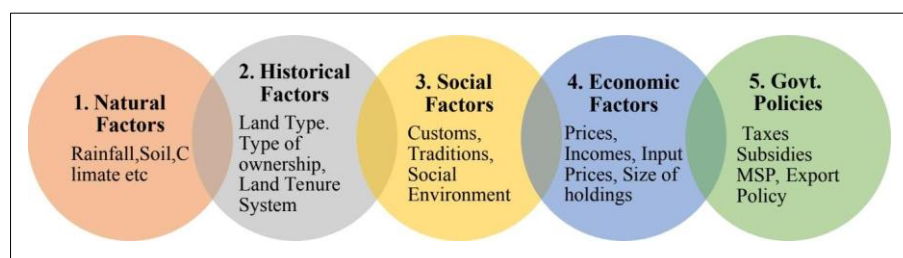


Fig 3: Factors Influencing Cropping Pattern

7. Impact of INM on Soil Health and its properties

The significance of increasing the availability of both applied and native soil nutrients to ensure balanced nutrition for crops is emphasized throughout the text. This method enhances and maintains the physical, chemical and biological performance of the soil reduces the detrimental impacts of hidden shortages and nutrient imbalances and promotes carbon sequestration, which lowers nutrient losses to the atmosphere and ground and surface water bodies (Hasanain *et al.*, 2020) ^[31]. Effect of integrated nutrient management on soil physical, chemical and biological properties (Dhaliwal *et al.*, 2021) ^[32].

7.1 Influence of INM on the physicochemical properties of soil

Integrated Nutrient Management (INM) profoundly enhances the physical and chemical environment of the soil. A key improvement is in soil structure, where Farmyard Manure (FYM) treatments have been shown to reduce soil bulk density while simultaneously increasing total porosity and water vapor content (Salehi *et al.*, 2017) ^[33]. This improvement is largely attributed to soil particle-binding agents like polysaccharides and bacterial gums released during the decomposition of organic manure (Meena *et al.*, 2018) ^[34]. As noted by Dhaliwal *et al.*, (2021) ^[32],

"FYM supplementation improved soil structural characteristics, positively influencing water vapor content," which is critical for root growth and water retention. Furthermore, INM significantly alters soil chemistry. The application of FYM can modify soil pH, a change driven by "organic acid release during FYM decomposition" (Katkar *et al.*, 2012) ^[35] and the oxidation of organic matter which releases carbon dioxide (Liang *et al.*, 2012) ^[36]. In contrast, the sole use of chemical fertilizers can have adverse effects, as "NPK fertilizers increased EC, leading to increased salt accumulation in soil" (Meena *et al.*, 2019) ^[37], highlighting the balancing role of organic amendments in INM.

7.2 Impact of INM on available and total NPK in soil

The synergy between organic and inorganic sources in INM is crucial for the availability and retention of primary macronutrients. For nitrogen, INM practices improve available N levels, partly due to the mineralization of fertilizers, but more sustainably through FYM, which provides a slow-release organic nutrient source (Hashim *et al.*, 2017) ^[38]. The role of FYM in nutrient cycling is multifaceted; it "improves metal ion complexation, increasing nutrient bioavailability" and "converts non-available plant nutrients to available ones and releases carbon

slowly" (Bhatt *et al.*, 2018) ^[39]. This leads to a strong correlation where total N increases with organic carbon content, with the highest levels often observed in treatments combining organic sources with recommended NPK fertilizers (Dhaliwal *et al.*, 2021) ^[32]. For phosphorus, FYM addition is a key strategy. It "increases available P content by mineralizing or solubilizing native P reserves" (Ahmad *et al.*, 2013) ^[10], thereby enhancing the soil's nutrient retention capacity and improving crop productivity (Rajneesh *et al.*, 2017) ^[40]. Specifically, "FYM acts as a P source and facilitates P retention in soil" (Mondal *et al.*, 2016) ^[41]. The benefits extend to potassium, where FYM application leads to decreased K fixation and a subsequent increase in accessible K. This is because "FYM's interaction with clay may contribute to improved total K content" (DV *et al.*, 2019) ^[42], and it "retains K ions on decomposed products, reducing leaching loss" (Dhaliwal *et al.*, 2021) ^[32], ensuring a more stable potassium supply for crops.

7.3 Impact of INM on DTPA-extractable and total micronutrients in soil

INM practices are equally critical for the management of essential micronutrients, preventing their deficiency in intensively cultivated soils. The application of FYM consistently increases the availability of zinc, as it plays a direct role in the soil Zn supply and dissolution. An observed "increase in total Zn content may be linked to Zn supplementation via chemical fertilizer and organic manure" (Zhang *et al.*, 2015) ^[5], demonstrating the complementary nature of INM. For copper, FYM

supplementation boosts available Cu by reducing the soil's redox potential and facilitating complexation with organic molecules during its decomposition. The combined use of "FYM in conjugation with chemical fertilizers increases total Cu in soil," as the "FYM addition forms organic chelates, reducing Cu ion retention and increasing microorganism populations" (Dhiman *et al.*, 2019) ^[43]. Similarly, iron availability is enhanced because "FYM increases Fe availability due to soil pH decrease and soil redox potential enhancement". Finally, FYM application is highly effective for manganese, leading to a buildup of DTPA-extractable Mn. This is "mainly due to manure supply and FYM decomposition, which also promotes Mn mobilization from solid phase to soil solution" (Dhaliwal *et al.*, 2013) ^[44], making this vital micronutrient more accessible to plant roots.

8. Impact of INM on millet growth, yield and quality

8.1 Effects on plant nutrient uptake and root development

The use of inorganic and organic fertilizers at the required dosage is one of the many elements that affect plant development. Additionally, INM enhances plant vigor, soil quality, and nutrient-use efficiency. According to studies, INM is crucial for enhancing agricultural output, lowering water use, conserving water, and promoting sustainable plant development. It is possible to attain high crop yields even in the absence of additional NPK treatment above the suggested dosage (Selim, 2020) ^[45]. The combined application of boron, sulfur, and farmyard manure with 75% NPK (N-150, P-60 and K-60) enhanced total nutrient absorption (Reena *et al.*, 2017; Sharma *et al.*, 2020) ^[46, 47].

Table 3. Summary of Studies on Integrated Nutrient Management (INM) in Different Millets.

Crops	Study areas	Salient features of the research
Pearl millet	India	The RDF (120 kg N + 45 kg P + 45 kg K + 20 kg ZnSO ₄ ha ⁻¹) produced more grain and fodder yield of pearl millet and the treatment remained at par with 50% RDF + 5 t ha ⁻¹ FYM + bio-fertilizer (Kadam <i>et al.</i> , 2019)
	Zimbabwe	Cattle manure with a combination of either biomass transfer and/or ammonium nitrate showed increases of soil fertility parameters, panicle length and grain yields (Kokerai <i>et al.</i> , 2019) ^[48]
	India	The application of 50% RDF, FYM, vermicompost, and V3-Badshah-6668 resulted in the maximum plant height, measuring 168.84 cm. (Deepshikha <i>et al.</i> , 2024) ^[49]
Foxtail millet	India	Application of 75% RDN (chemical) + 25% N (poultry manure) + seed inoculation with <i>Azospirillum</i> increased grain yield (Selectstar <i>et al.</i> , 2019) ^[50]
	India	Integrated application of FYM + RDF + 3% Panchagavya produced more grains than RDF (Kumaran and Parasuraman, 2019) ^[51]
	India	Application of 50% RDF (through chemicals) + 25% N (through neem cake) + microbial fertilizer registered more yield than only RDF (Monisha <i>et al.</i> , 2019) ^[52]
Little millet	India	Combined application of 75% RDN (chemical) + 25% RDN (vermicompost) yielded more than RDF (Thesiya <i>et al.</i> , 2019) ^[53]
	India	A combination of 100% RDF + 1 t ha ⁻¹ neem ensured higher yield than RDF (Sandhya <i>et al.</i> , 2017) ^[54]
Kodo millet	India	Application of 100% NPK fertilizer (40 kg N, 20 kg P ₂ O ₅ , and 10 kg K ₂ O ha ⁻¹) gave maximum panicles (6.56/plant), grains count (237.5/panicle), panicle length (14.86 cm), grain weight (1.24 g/panicle), and test weight (6.36 g), grain yield of 27.55 q ha ⁻¹ (Choudhari <i>et al.</i> , 2018) ^[55]
Finger millet	India	100% RDF application increases finger millet growth and productivity but not crop productivity and long-term biofertilizer improves soil health, while one-season application has little effect on growth (Ramya <i>et al.</i> , 2020) ^[56]
	India (Odisha)	There was improvement of plant height and yield attributes with 90 kg N ha ⁻¹ than lower levels (0, 30 and 60 kg ha ⁻¹). An increase in phosphorus levels from 20 to 40 kg ha ⁻¹ enhanced productivity. A combination of 90 kg N and 40 kg P ha ⁻¹ registered the highest grain and straw yield (1054 and 4369 kg ha ⁻¹ respectively) (Vamshi <i>et al.</i> , 2019) ^[57]
	India (South Odisha)	The highest grain yield was achieved from the treatment with 100% RDF at 40-20-20 kg N, P ₂ O ₅ and K ₂ O ha ⁻¹ (1412 kg ha ⁻¹) compared to control (without any nutrient) with grain yield of 637 kg ha ⁻¹ (Harika <i>et al.</i> , 2019) ^[58]
	India	Combined application of 10 t ha ⁻¹ FYM + bio fertilizer consortia (<i>Azospirillum</i> brasilense + <i>Bacillus</i> spp. + <i>Psuedomonas</i> fluorescence at 20 g kg ⁻¹ seed each) + ZnSO ₄ (12.5 kg ha ⁻¹) + Borax (kg ha ⁻¹) + 100% RDF (50:30:25) yielded more than RDF in sandy loam soil (Roy <i>et al.</i> , 2018) ^[59]
Sorghum	India	100% RDF + 10 t FYM ha ⁻¹ treatment showed the highest growth, yield attributes and nutrient uptake among all treatments, resulting in the highest sorghum grain yield (2416 kg ha ⁻¹) and gross return (₹85108/- ha ⁻¹) (Tudu <i>et al.</i> , 2023) ^[60]
	India	Application of 75% RDN through inorganic fertilizer + 25% RDN through vermicompost + seed treatment with PSB + <i>Azospirillum</i> gave significantly higher GMR (₹76,068 ha ⁻¹), NMR (₹37,999 ha ⁻¹) and B:C ratio of 2.07 (Sallawar <i>et al.</i> , 2023) ^[61]

8.2 Effects of INM on Crop Quality

PHB-3 cultivars had the greatest nutritional content, protein content, protein yield and water productivity and the maximum nutritional content was found with 75% RDF + Biofertilizers at 5

kg ha⁻¹ incubated with vermicompost at 500 kg ha⁻¹ (Krishnaprabu, 2019)^[62]. As summarized in Table 4, millets serve as a rich source of diverse nutritional components, exemplified by millets (Kadapa *et al.*, 2023)^[63].

Table 4. Millets as a rich source of nutritional contents

Sr. No.	Millet	Nutritional Content
I.	Pearl millet	Compared with other millets, it has higher levels of lysine, zinc and iron (17-65 mg g ⁻¹ of protein). The soluble phenolic fraction has ferulic acid equivalents and a total reported phenolic value of 168 mg/100 g (pearl millet). The soluble phenolic fraction had a total flavonoid concentration of 49 mg/100 g (pearl millet) catechin equivalents.
II.	Foxtail millet	A substantial amount of fat (4%) and protein (11%). The protein fractions are represented by prolamins (39.4%), glutelins (9.9%), albumins and globulins (13%). As a result, it is suggested as the perfect diet for diabetics. Additionally, it has high concentrations of carotenoids, phenols and phenolic acids, which are possible antioxidants.
III.	Finger millet	In comparison to other millets, it is higher in Fe, Zn and lysine (17-65 mg g ⁻¹ of protein). The soluble phenolic fraction's catechin equivalents and total flavonoid levels have been observed to be between 203 and 228 mg/100 g (finger millet).
IV.	Proso millet	Compared to other millets, it has higher levels of Fe, Zn and lysine (17-65 mg g ⁻¹ of protein). Pearl millet has a reported total phenolic concentration of 168 mg/100 g and the soluble phenolic fraction contains equivalents of ferulic acid. The soluble phenolic fraction's total flavonoid levels have been found to be 140 mg/100 g (proso millet) catechin equivalents.
V.	Barnyard millet	Functional components, such as β -glucan and γ -aminobutyric acid (GABA), which lower blood lipid levels and act as antioxidants.
VI.	Kodo millet	A high concentration of magnesium (1.1 g/kg dry matter).
VII.	Overall view of millets	They include health-promoting flavonoids and phenolic acids, which are essential for reducing blood glucose levels and preventing oxidative stress caused by free radicals.

8.3 Mechanisms of integrated nutrient management (INM) in millet production

Integrated Nutrient Management (INM) enhances millet productivity through the synergistic interaction of organic manures, inorganic fertilizers, and biological inputs, resulting in improved nutrient availability and nutrient-use efficiency. Organic amendments such as farmyard manure, compost, vermicompost, and crop residues increase soil organic carbon, improve soil aggregation, enhance water-holding capacity, and stimulate microbial activity, thereby creating a favorable rhizosphere for crop growth (Dhaliwal *et al.*, 2021; Madhurya *et al.*, 2022)^[32, 13]. Biofertilizers, including *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria (PSB), and arbuscular mycorrhizal fungi (AMF), improve nutrient acquisition through biological nitrogen fixation, phosphorus solubilization, potassium mobilization, and the production of plant growth promoting substances such as auxins, gibberellins, and cytokinins (Basu *et al.*, 2021; Bhardwaj *et al.*, 2014)^[15, 16]. The balanced application of inorganic fertilizers together with organic and biological nutrient sources ensures synchronized nutrient release throughout the crop growth cycle, thereby reducing nutrient losses through leaching, volatilization, and denitrification while enhancing fertilizer-use efficiency (Bindraban *et al.*, 2015; Vanlauwe *et al.*, 2015)^[64, 65]. In millet production systems, INM also promotes extensive root development, greater nutrient uptake, enhanced photosynthetic efficiency, and improved assimilate translocation, resulting in superior grain yield and quality. Furthermore, improved soil biological activity accelerates nutrient cycling and enhances the availability of both macro- and micronutrients, contributing to sustainable productivity under rainfed and marginal environments (Paramesh *et al.*, 2023; Sande *et al.*, 2024)^[23, 66].

9. Environmental benefits of integrated nutrient management

Integrated Nutrient Management contributes significantly to environmental sustainability by reducing dependence on synthetic fertilizers and improving nutrient-use efficiency. Balanced nutrient application minimizes nitrogen losses through ammonia volatilization, nitrate leaching, and nitrous oxide NO₂ emissions, thereby reducing greenhouse gas emissions and

environmental pollution (Carlson *et al.*, 2017; Paramesh *et al.*, 2023)^[67, 23]. Organic nutrient sources enhance soil carbon sequestration, improve soil biodiversity, and increase microbial biomass, which collectively contribute to long-term soil fertility and ecosystem resilience (Dhaliwal *et al.*, 2021)^[32]. The recycling of crop residues, animal manures, and organic wastes within INM decreases waste accumulation while promoting circular nutrient cycling. Improved soil structure resulting from organic amendments enhances water infiltration, reduces runoff and soil erosion, and increases drought resilience in millet-based production systems (Madhurya *et al.*, 2022)^[13]. Furthermore, diversified cropping systems involving legumes improve biological nitrogen fixation, reduce external fertilizer requirements, and strengthen agroecosystem sustainability. Consequently, INM supports climatesmart agriculture by increasing productivity while minimizing adverse environmental impacts and conserving natural resources for future generations (Ravikumar *et al.*, 2021; Sande *et al.*, 2024)^[68, 66].

10. Emerging technologies in integrated nutrient management

Recent advances in digital agriculture have transformed Integrated Nutrient Management by enabling precise, site-specific, and data-driven nutrient management practices. Artificial Intelligence (AI) facilitates nutrient deficiency diagnosis, fertilizer recommendation, yield prediction, and decision support through machine learning algorithms trained on soil, crop, and climatic datasets (Basso and Antle, 2020; Liakos *et al.*, 2018)^[69, 70]. Geographic Information Systems (GIS) combined with Global Positioning Systems (GPS) enable spatial mapping of soil fertility, identification of nutrient-deficient zones, and development of variable-rate fertilizer application strategies, thereby improving nutrient-use efficiency and reducing input costs (Mulla, 2013; Paramesh *et al.*, 2023)^[71, 23].

Remote sensing technologies using multispectral and hyperspectral satellite imagery enable rapid assessment of crop nutritional status, chlorophyll content, biomass accumulation, and early nutrient stress before visible symptoms appear, facilitating timely and site-specific nutrient management interventions (Kuldeep *et al.*, 2024)^[72]. Similarly, Unmanned Aerial Vehicles (UAVs) equipped with advanced sensors offer high-resolution

monitoring of crop growth, nutrient deficiencies, and spatial variability, supporting precision fertilizer application and improving field-scale nutrient management (Tsouros *et al.*, 2019)^[73]. Internet of Things (IoT)-based sensors continuously monitor soil moisture, nutrient status, temperature, and environmental conditions, enabling real-time nutrient management and automated decision-making (Jawad *et al.*, 2017)^[74]. The integration of these digital technologies with conventional INM practices is expected to enhance nutrient-use efficiency, reduce fertilizer losses, improve millet productivity, and promote climate-resilient, sustainable agricultural systems.

11. Environmental and economic considerations

Anthropogenic GHG emissions must be controlled by proper fertilizer management and integrated nutrient management (INM) has been shown to be more successful than alternative techniques (Carlson *et al.*, 2017)^[67]. Uncontrolled fertilizer usage raises atmospheric emissions and nutrient leaching into groundwater. The INM encourages high agricultural yields while lowering nitrogen losses and the related negative environmental effects (Paramesh *et al.*, 2023)^[23]. Crop nutrient intake, immobilization, and soil residues, together with nitrogen losses to the environment through ammonia volatilization, NOX emissions, denitrification, N leaching, and runoff, all contribute to the final destiny of applied fertilizers (Wu and Ma, 2015)^[75]. Diversified cropping systems, fertilizer recycling and reuse plans, and precision nutrient management approaches may all be created to reduce environmental contamination. By capturing nutrients from sources such as livestock manure and agricultural leftovers, these methods reduce nutrient losses and transform them into useful organic amendments. Crop rotation and intercropping can help cut down on the need for synthetic nitrogen fertilizer (Paramesh *et al.*, 2023)^[23]. Agriculture and related systems will contribute significantly to global greenhouse gas emissions. Nutrient recycling and reuse techniques in INM effectively collect and recycle nutrients from a variety of sources, including wastewater, livestock manure, and agricultural leftovers (Ravikumar *et al.*, 2021)^[68].

12. Challenges

The greatest challenge in sustainable agriculture is not producing more, but producing more with fewer resources while conserving the environment.

- i) **Declining soil fertility:** Continuous cultivation, nutrient mining, and imbalanced fertilizer use deplete soil organic matter and essential nutrients, reducing nutrient-use efficiency, soil fertility, and millet productivity. Low soil organic carbon further limits sustainable production, particularly in rainfed and marginal agroecosystems (Vanlauwe *et al.*, 2019; Chivenge *et al.*, 2021)^[76, 77].
- ii) **Low adoption of INM technologies:** Despite its proven benefits, the adoption of Integrated Nutrient Management (INM) in millet cultivation remains limited due to inadequate farmer awareness, weak extension services, poor access to quality biofertilizers and organic inputs, insufficient soil-testing facilities, and resource constraints among smallholder farmers (FAO, 2023; Warisa *et al.*, 2025)^[16, 1].
- iii) **Variable performance of biological inputs:** The effectiveness of biofertilizers, plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and microbial consortia varies with soil, climate, and management practices. Environmental factors often cause inconsistent field performance, limiting their reliability and adoption by farmers (Basu *et al.*, 2021)^[15].

- iv) **Climate change, environmental stresses and socio-economic challenges:** Climate change has become one of the most serious threats to sustainable agriculture. Rising temperatures, erratic rainfall, increasing atmospheric CO₂ concentrations, frequent droughts, and extreme weather events adversely affect nutrient availability, fertilizer-use efficiency, and microbial activity in millet production systems (Hossain *et al.*, 2021; Bhadra *et al.*, 2021; Lal, 2020)^[79, 78, 82]. Although millets are naturally climate-resilient and suitable for marginal environments, they continue to suffer from low consumer demand and negative perceptions as "poor people's food." Their acceptance is further constrained by coarse texture, longer cooking time, susceptibility to pests and birds, and post-harvest nutrient losses, limiting their commercial potential despite their superior nutritional value (Kumar *et al.*, 2018; Srivastava *et al.*, 2023)^[80, 81].
- v) **Economic and infrastructural constraints:** The adoption of precision agriculture, nano-fertilizers, remote sensing, AI-based nutrient advisory systems, and digital decision-support tools is limited by high costs, inadequate infrastructure, poor internet connectivity, and weak policy support, particularly among smallholder farmers in developing countries (Jat *et al.*, 2023; Kumar *et al.*, 2024)^[9, 49].

13. Future Perspectives

The future of agriculture lies in integrating science, technology, and ecological principles to achieve sustainable food security.

- i) **Precision and digital nutrient management:** Future INM strategies should integrate artificial intelligence (AI), remote sensing, drones, Geographic Information Systems (GIS), Internet of Things (IoT) sensors, and digital decision-support systems to enable real-time monitoring of crop nutrient status and site-specific fertilizer application. These technologies can significantly improve nutrient-use efficiency while minimizing production costs and environmental pollution (Jat *et al.*, 2023; Kumar *et al.*, 2024)^[9, 49].
- ii) **Development of climate-smart INM:** Climate-smart integrated nutrient management should focus on combining organic manures, conservation agriculture, biofertilizers, precision nutrient application, and resilient cropping systems to enhance soil health, carbon sequestration, nutrient cycling, and resilience against drought and other climate-induced stresses. Long-term field experiments are required to evaluate the sustainability of these integrated approaches under diverse agroecological conditions (Chivenge *et al.*, 2021; Lal, 2020)^[77, 82].
- iii) **Advanced biological inputs and nutrient-efficient technologies:** Future research should emphasize the development of highly efficient microbial consortia, PGPR, AMF, biochar-based nutrient formulations, and nano-enabled biofertilizers to improve nutrient availability, soil microbial diversity, and crop productivity. The integration of these biological inputs with conventional fertilizers will strengthen sustainable nutrient management in millet-based production systems (Basu *et al.*, 2021; Raliya *et al.*, 2018)^[15, 89].
- iv) **Research, innovation and sustainable millet production:** Compared with rice, wheat, and maize, nutrient management research in millets remains limited. Future studies should prioritize precision nutrient management, improved nitrogen-use efficiency, nano-fertilizers, digital agriculture, and integrated nutrient strategies to enhance millet productivity and support climate-smart, sustainable food systems (Tiwari *et al.*, 2023; Dimkpa & Bindraban, 2018)^[83, 85].

- v) **Policy support, awareness and global food security:** With the global population expected to reach 9.7 billion by 2050, collaborative efforts among governments, researchers, NGOs, and the private sector are essential to promote advanced INM, improve millet production, strengthen food and nutritional security, enhance farmer income, and ensure environmental sustainability (FAO, 2023; Sahoo *et al.*, 2023; Warisa *et al.*, 2025) ^[84, 6, 1].

14. Conclusion

Integrated Nutrient Management (INM) is essential for enhancing millet crop development, yield, and quality, particularly when dealing with nutrient imbalances, soil degradation, and climatic variability. By improving nutrient availability, encouraging soil microbial activity, and raising the amount of organic matter in the soil, advanced INM techniques, which incorporate organic inputs, inorganic fertilizers, and biological amendments, improve soil health. Higher yields and better grain quality results from this. By increasing soil fertility and decreasing reliance on synthetic fertilizers, INM not only increases agricultural output but also supports long-term sustainability. Additionally, it lessens the danger of soil erosion, enhances nutrient cycling, and reduces the negative environmental effects of traditional agricultural methods. There are still issues, though, such as resource access, farmer knowledge, and region-specific nutrient management techniques. Future studies should concentrate on improving INM procedures, creating affordable fixes, and encouraging farmer adoption through training initiatives and extension services.

15. Limitations

This review has several limitations. First, it is based on a structured narrative review rather than a quantitative meta-analysis; therefore, the overall magnitude of treatment effects and publication bias could not be statistically assessed. Second, many of the reviewed studies were conducted on specific millet species and under particular agroecological conditions, limiting the broader applicability of the findings across diverse climates, soils, and production systems. Third, the effectiveness of integrated nutrient management (INM) components, including organic manures, biofertilizers, microbial consortia, nano-fertilizers, and micronutrients, is influenced by variations in soil properties, climatic conditions, crop genotype, and management practices. Furthermore, emerging digital technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), Artificial Intelligence (AI), Internet of Things (IoT), and Unmanned Aerial Vehicles (UAVs) have primarily been evaluated under experimental or pilot-scale conditions, with limited long-term field validation in millet production systems. Future research should prioritize multi location and long-term experiments, standardized methodologies, economic feasibility analyses, and largescale on-farm validation to improve the reliability, scalability, and adoption of advanced INM strategies in sustainable millet cultivation.

References

- Food and Agriculture Organization of the United Nations. International Year of Millets 2023. 2023. <https://www.fao.org/millets-2023/en/>
- Maitra S, Shankar T, Hossain A, Sairam M, Sagar L, Sahoo U, *et al.* Climate-smart millets production in future for food and nutritional security. In *Adapting to climate change in agriculture theories and practices: Approaches for adapting to climate change in agriculture in India*. Cham: Springer Nature Switzerland; 2024:11-41.
- Banerjee P, Maitra S. The role of small millets as functional food to combat malnutrition in developing countries. *Indian Journal of Natural Sciences*. 2020;10(60):20412–20417.
- Brahmachari K, Sarkar S, Santra DK, Maitra S. Millet for food and nutritional security in drought prone and red laterite region of eastern India. *International Journal of Plant Soil and Science*. 2018;26(6):1–7.
- Zhang T, Yu S, Pan Y, Li H, Liu X, Cao J. Properties of texturized protein and performance of different protein sources in the extrusion process: a review. *Food Res. Int*. 2023;174:113588. <https://doi.org/10.1016/j.foodres.2023.113588>
- Warisa S, Debbarma A, Hazarika A, Nath AJ. Millet cultivation in India: geographical distribution, nutrient management practices, and policy implications. *Discover Soil*. 2025;2(1):12.
- Hasanath T, Bindhu JS, Pillai PS, John J, Meera AV, Archana B. Agronomic Interventions for Optimizing Productivity in Millets: A Review. *Agricultural Reviews*. 2026;47(1):100-105.
- Nithiyanantham S, Kalaiselvi P, Mahomoodally MF, Zengin G, Abirami A, Srinivasan G. Nutritional and functional roles of millets-a review. *J. Food Biochem*. 2019;43:e12859. <https://doi.org/10.1111/jfbc.12859>
- Jat LK, Singh YV, Meena SK, Meena SK, Parihar M, Jatav HS, Meena VS. Does integrated nutrient management enhance agricultural productivity. *J Pure Appl Microbiol*. 2015;9(2):1211-1221.
- Ahmad W, Shah Z, Khan F, Ali S, Malik W. Maize yield and soil properties as influenced by integrated use of organic, inorganic, and bio-fertilizers in a low fertility soil. *Soil and Environment*. 2013;32(2):121–129.
- Anitha S, Givens DI, Botha R, Kane-Potaka J, Sulaiman NLB, Tsusaka TW, *et al.* Calcium from finger millet: a systematic review and meta-analysis on calcium retention, bone resorption, and *in vitro* bioavailability. *Sustainability*. 2021;13(16):8677.
- Harish MS, Bhuker A, Chauhan BS. Millet production, challenges, and opportunities in the Asiapacific region: a comprehensive review. *Frontiers in Sustainable Food Systems*. 2024;8:1386469.
- Madhurya P, Latha M, Rao CS, Sree SP. Effect of integrated nutrient management on physical and physico-chemical properties of soil. *International Journal of Plant & Soil Science*. 2022;34(24):1028-1033.
- Das R, Biswas S. Role of integrated nutrient management on oat: A review. *International Journal of Environment and Climate Change*. 2022:66-79.
- Basu A, Prasad P, Das SN, Kalam S, Sayyed RZ, Reddy MS, *et al.* Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects. *Sustainability*. 2021;13(3):1140.
- Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N. Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial cell factories*. 2014;13(1):66.
- Raj S, Chaudhary S, Ghule NS, Baral K, Padhan SR, Gawande KN, *et al.* Sustainable farming and soil health enhancement through millet cultivation: A review. *Int. J. Plant Soil Sci*. 2024;36(3):222-233.
- Jacob J, Krishnan V, Antony C, Bhavyasri M, Aruna C, Mishra K, *et al.* The nutrition and therapeutic potential of millets: an updated narrative review. *Frontiers in nutrition*. 2024;11:1346869.

19. Ghosh K, Vinodkumar T, Singh R, Singh A, Ilavarasan R. Promising potential of millets as the staple of our plate: An Indian perspective. *Discover Food*. 2024;4(1):103.
20. Mehta D, Vyas S, Dudhagara D, Patel A, Parmar V. Significance of Indian millets in enhancing global food security: A comprehensive review. *Trends in Food Science & Technology*. 2024;149:104527.
21. Kumar A, Pramanik J, Jangra A, Prajapati B, Kumar S, Mehra R. Nourishment beyond grains: Unveiling the multifaceted contributions of millets to United Nations Sustainable Development Goals. *Zeitschrift für Naturforschung C*. 2025;80(5-6):151-162.
22. Louhar G, Bana RS, Kumar V, Kumar H. Nutrient management technologies of millets for higher productivity and nutritional security. *The Indian Journal of Agricultural Sciences*. 2020;90(12):2243-2250.
23. Paramesh V, Mohan Kumar R, Rajanna GA, Gowda S, Nath AJ, Madival Y, *et al.* Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Frontiers in Sustainable Food Systems*. 2023;7:1173258.
24. Panta S, Parajulee D. Integrated Nutrient Management (INM) in soil and sustainable agriculture. *International Journal of Applied Sciences and Biotechnology*. 2021;9(3):160-165.
25. Guo Z, Zhang J, Fan J, Yang X, Yi Y, Han X, *et al.* Does animal manure application improve soil aggregation? Insights from nine long-term fertilization experiments. *Science of the Total Environment*. 2019;660:1029-1037.
26. Puig CG, Revilla P, Barreal ME, Reigosa MJ, Pedrol N. On the suitability of *Eucalyptus globulus* green manure for field weed control. *Crop Protection*. 2019;121:57-65.
27. Singh SK, Singh J, Rajveer, Simon S, Choudhary N. Growth Factors for a Strawberry Crop are Affected by Microalgae and Vermicompost. *Journal of Experimental Agriculture International*. 2023;45(9):177-181. <https://doi.org/10.9734/jeai/2023/v45i92189>
28. Hazarika J, Pradhan S, Borthakur PK, Sharma S. INM: A key for soil health and sustainable agriculture. *Sustainable Management of Soil Health*. 2023;40.
29. Jote CA. The impacts of using inorganic chemical fertilizers on the environment and human health. *Organ Med Chem Intl J*. 2023;13(3):555864.
30. Sukanya TS, Kumar A, Narayanan AL, Sathya K, Kishore K, Shyam M, *et al.* Cropping systems for sustainable millet production. In *Adapting to Climate Change in Agriculture-Theories and Practices: Approaches for Adapting to Climate Change in Agriculture in India*. Cham: Springer Nature Switzerland; 2024:269-280.
31. Hasanain M, Fatima A, Yadav R. Integrated Nutrient Management for Improve soil health. *Agriculture and Food: e-Newsletter*. 2020;2(3):543-547.
32. Dhaliwal SS, Sharma S, Sharma V, Shukla AK, Walia SS, Alhomrani M, *et al.* Longterm integrated nutrient management in the maize–wheat cropping system in alluvial soils of North-Western India: Influence on soil organic carbon, microbial activity and nutrient status. *Agronomy*. 2021;11(11):2258.
33. Salehi A, Fallah S, Sourki AA. Organic and inorganic fertilizer effect on soil CO₂ flux, microbial biomass, and growth of *Nigella sativa* L. *International Agrophysics*. 2017;31(1).
34. Meena KB, Alam MS, Singh H, Bhat MA, Singh AK, Mishra AK, *et al.* Influence of farmyard manure and fertilizers on soil properties and yield and nutrient uptake of wheat. *International Journal of Chemical Studies*. 2018;6(3):386-390.
35. Katkar RN, Kharche VK, Sonune BA, Wanjari RH, Singh M. Long-term effect of nutrient management on soil quality and sustainable productivity under sorghum-wheat crop sequences in vertisols of Akola, Maharashtra. *Agropedology*. 2012;22(2):103–114.
36. Liang Q, Chen H, Gong Y, Fan M, Yang H, Lal R, *et al.* Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. *Nutrient Cycling in Agroecosystems*. 2012;92(1):21–33. <https://doi.org/10.1007/s10705-012-9470-0>
37. Meena BP, Biswas AK, Singh M, Chaudhary RS, Singh AB, Das H, *et al.* Long-term sustaining crop productivity and soil health in maize–chickpea system through integrated nutrient management practices in Vertisols of central India. *Field crops research*. 2019;232:62-76.
38. Hashim M, Dhar S, Vyas AK, Singh CB. Yield trends and changes in physico-chemical properties of soil in maize-wheat cropping system under integrated nutrient management. *Journal of Environmental Biology*. 2017;38(4):727–734.
39. Bhatt MK, Raverkar KP, Labanya R, Bhatt CK. Effects of long-term balanced and imbalanced use of inorganic fertilizers and organic manure (FYM) on soil chemical properties and yield of rice under ricewheat cropping system. *Journal of Pharmacognosy and Phytochemistry*. 2018;7(3):703–708.
40. Rajneesh, Sharma RP, Sankhyan N, Kumar RV. Long-Term Effect of Fertilizers and Amendments on Depth-Wise Distribution of Available NPK, Micronutrient Cations, Productivity, and NPK Uptake by Maize-Wheat System in an Acid Alfisol of NorthWestern Himalayas. *Communications in Soil Science and Plant Analysis*. 2017;48:2193-2209.
41. Mondal S, Mallikarjun M, Ghosh M, Ghosh DC, Timsina J. Influence of integrated nutrient management (INM) on nutrient use efficiency, soil fertility and productivity of hybrid rice. *Archives of Agronomy and Soil Science*. 2016;62(11):1521-1529.
42. DV P, Krishnamurthy R, Naveen DV. Long-term effect of integrated nutrient management on soil nutrient status, content and uptake by finger millet crop in a typical kandiusalt of eastern dry zone of Karnataka. *Communications in Soil Science and Plant Analysis*. 2020;51(2):161-174.
43. Dhiman D, Sharma R, Sankhyan NK, Sepehya S, Sharma SK, Kumar R. Effect of regular application of fertilizers, manure, and lime on soil health and productivity of wheat in an acid Alfisol. *Journal of Plant Nutrition*. 2019;42(22):2507–2521.
44. Dhaliwal SS, Manchanda JS, Walia SS, Dhaliwal MK. Differential response of manures in transformation of DTPA and total zinc and iron in rice transplanted on light-textured soils of Punjab. *International Journal of Science and Environment Technology*. 2013;2(2):300–312.
45. Selim MM. Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. *International Journal of Agronomy*. 2020;(1):2821678.
46. Reena, Pandey SB, Tiwari DD, Nigam RC, Singh AK, Kumar S. Effect of INM on yield and nutrient uptake of wheat and soil health. *International Archive of applied sciences and technology*. 2017;8(3):25-28.
47. Sharma S, Kandel N, Chaudhary P, Rai P. A Review on Integrated Nutrient Management on Wheat (*Triticum*

- Aestivum L.). Reviews in Food and Agriculture (RFNA). 2020;1(1):32-37.
48. Kokera LK, Kugedera AT, Chimbwanda F. Evaluation of economic returns of insitu rainwater harvesting and integrated nutrient management options on sorghum production. *Amity Journal of Agribusiness*. 2019;3(2):36–46.
 49. Deepshikha LKS, Singh V, Kumar A, Singh V, Kushwaha A. Response of integrated nutrient management (INM) and different varieties on growth and yield of pearl millet (*Pennisetum glaucum* L.). *International Journal of Research in Agronomy*. 2024;7(6):145–148.
 50. Selectstar Marwein B, Singh R, Chhetri P. Effect of integrated nitrogen management on yield and economics of foxtail millet genotypes. *International Journal of Current Microbiology and Applied Sciences*. 2019;8(08):2543-2546.
 51. Kumaran G, Parasuraman P. Effect of enriched FYM and Panchagavya spray on foxtail millet (*Setaria italica*) under rainfed conditions. *International Journal of Chemical Studies*. 2019;7(2):2121–2123.
 52. Monisha V, Rathinaswamy A, Mahendran PP, Kumutha K. Influence of integrated nutrient management on growth attributes and yield of foxtail millet in red soil. *International Journal of Chemical Studies*. 2019;7(3):3536–3539.
 53. Thesiya NM, Dobariya JB, Patel JG. Effect of integrated nutrient management on growth and yield parameters of kharif little millet under little millet-green gram cropping sequence. *International Journal of Pure and Applied Bioscience*. 2019;7(3):294–298. <https://doi.org/10.18782/2320-7051.7392>
 54. Sandhya Rani Y, Triveni U, Patro TSSK, Divya M, Anuradha N. Revisiting of fertilizer doses in finger millet (*Eleusine coracana* (L.) Gaertn.) Through targeted yield and soil test crop response (STCR), approach. *International Journal of Current Microbiology and Applied Sciences*. 2017;6(7):2211-2221.
 55. Choudhari MK, Tiwari RK, Mishra RM, Namdeo KN. Integrated nutrient management on growth, yield and economics of kodo millet (*Paspalum scrobiculatum* L.). *Ann Plant Soil Res*. 2018;20(4):405-408.
 56. Ramya P, Maitra S, Shankar T, Adhikary R, Palai JB. Growth and productivity of finger millet (*Eleusine coracana* L. Gaertn) as influenced by integrated nutrient management. *Agron Econ*. 2020;7:19-24.
 57. Vamshi Krishna K, Deepthi CH, Devender Reddy M, Raju PS, Pal A. Effect of nitrogen and phosphorus levels on growth and yield of finger millet (*Eleusine coracana* L. Gaertn) during summer. *Indian Journal of Agricultural Research*. 2019.
 58. Harika JV, Maitra S, Shankar T, Bera M, Manasa P. Effect of integrated nutrient management on productivity, nutrient uptake and economics of finger millet (*Eleusine coracana* L. Gaertn). *International Journal of Agriculture, Environment and Biotechnology*. 2019;12(3):273-279.
 59. Roy AK, Ali N, Lakra RK, Alam P, Mahapatra P, Narayan R. Effect of integrated nutrient management practices on nutrient uptake, yield of finger millet (*Eleusine coracana* L. Gaertn.) and post-harvest nutrient availability under the rainfed condition of Jharkhand. *International Journal of Current Microbiology and Applied Sciences*. 2018;7(08):339-347. <https://doi.org/10.20546/ijcmas.2018.708.038>
 60. Tudu AK, Palai JB, Shankar T, Adhikary R, Mondal T, Nath S. Effect of Integrated Nutrient Management on Growth, Yield, Nutrient Uptake and Economics of Rabi Sorghum (*Sorghum bicolor* L.). *International Journal of Environment and Climate Change*. 2023;13(10):4239-4247.
 61. Sallawar SC, Alse UN, Mane SG. Effect of Integrated Nutrient Management on Yield, Economics and Available Soil Nutrient of Kharif Sorghum (*Sorghum bicolor* L.). *International Journal of Environment and Climate Change*. 2023;13(8):881-888.
 62. Krishnaprabu S. Nutrient content, quality and water productivity of pearl millet in response to integrated nutrient management. *Research on Crops*. 2019;20(4):690-694.
 63. Kadapa S, Gunturi A, Gundreddy R, Kalwala SR, Mogallapu UB. Agronomic Biofortification of Millets: New Way to Alleviate Malnutrition. In *Millets-Rediscover Ancient Grains*. IntechOpen; 2023.
 64. Bindraban PS, Dimkpa C, Nagarajan L, Roy A, Rabbinge R. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. *Biology and Fertility of Soils*. 2015;51(8):897-911.
 65. Vanlauwe B, Descheemaeker K, Giller KE, Huising J, Merckx R, Nziguheba G, et al. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil*. 2015;1(1):491-508.
 66. Sande TJ, Tindwa HJ, Alovizi AMT, Shitindi MJ, Semoka JM. Enhancing sustainable crop production through integrated nutrient management: a focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilisers—a systematic review. *Frontiers in Agronomy*. 2024;6:1422876.
 67. Carlson KM, Gerber JS, Mueller ND, Herrero M, MacDonald GK, Brauman KA, et al. Greenhouse gas emissions intensity of global croplands. *Nature Climate Change*. 2017;7(1):63-68.
 68. Ravikumar C, Ravikumar M, Karthikeyan A, Senthilvalavan P, Manivannan R. Integrated nutrient management-promising way to reduce carbon dioxide and methane emission in flooded rice ecosystem: A review. *Journal of Applied & Natural Science*. 2021;13(1):385-395.
 69. Basso B, Antle J. Digital agriculture to design sustainable agricultural systems. *Nature sustainability*. 2020;3(4):254-256.
 70. Liakos KG, Busato P, Moshou D, Pearson S, Bochtis D. Machine learning in agriculture: A review. *Sensors*. 2018;18(8):2674.
 71. Mulla DJ. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*. 2013;114(4):358-371.
 72. Kuldeep, Singh AK, Sajwan A, Kamboj AD, Joshi G, Gautam R, Kaur J. Advances in precision nutrient management of fruit crops. *Journal of Plant Nutrition*. 2024;47(19):3251-3271.
 73. Tsouros DC, Bibi S, Sarigiannidis PG. A review on UAV-based applications for precision agriculture. *Information*. 2019;10(11):349.
 74. Jawad HM, Nordin R, Gharghan SK, Jawad AM, Ismail M. Energy-efficient wireless sensor networks for precision agriculture: A review. *Sensors*. 2017;17(8):1781.
 75. Wu W, Ma B. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. *Sci. Total Environ*. 2015;512-513:415–427. <https://doi.org/10.1016/j.scitotenv.2014.12.101>
 76. Vanlauwe B, Chivenge P, Zingore S. Soil fertility maintenance and nutrient management for agricultural transformation. *Transforming Agriculture in Southern Africa*. 2019:67-76. <https://doi.org/10.4324/9780429401701-11>

77. Chivenge P, Saito K, Bunquin MA, Sharma S, Dobermann A. Co-benefits of nutrient management tailored to smallholder agriculture. *Global Food Security*. 2021;30:100570. <https://doi.org/10.1016/j.gfs.2021.100570>
78. Bhadra P, Maitra S, Shankar T, Hossain A, Praharaj S, Aftab T. Climate change impact on plants: plant responses and adaptations. In: Aftab T, Roychoudhury A (Eds) *Plant perspectives to global climate changes*. Elsevier Inc., Academic Press; 2021:1–24. <https://doi.org/10.1016/>
79. Hossain A, Skalicky M, Brestic M, Maitra S, Ashraful Alam M, Syed MA, *et al.* Consequences and mitigation strategies of abiotic stresses in wheat (*Triticum aestivum* L.) under the changing climate. *Agronomy*. 2021;11:241. <https://doi.org/10.3390/agronomy11020241>
80. Kumar A, Tomer V, Kaur A, Kumar V, Gupta K. Millets: A solution to agrarian and nutritional challenges. *Agriculture and food security*. 2018;7(1):1-15.
81. Srivastava P, Sangeetha C, Baskar P, Mondal K, Bharti SD, Singh BV, *et al.* Unleashing the potential of millets promoting nutritious grains as vital cereal staples during the international year of millets: A review. *International Journal of Plant and Soil Science*. 2023;35(18):1860-1871.
82. Lal R. Eco-Intensification of agroecosystems to realize the sustainable development goals of the United Nations. *Journal of Natural Resource Conservation and Management*. 2020;1(2):83. <https://doi.org/10.51396/anrcm.1.2.2020.83-95>
83. Tiwari H, Naresh RK, Bhatt R, Kumar Y, Das D, Kataria SK. Underutilized nutrient rich millets: challenges and solutions for India's food and nutritional security: a review. *International Journal of Plant and Soil Science*. 2023;35(2):45-56.
84. Sahoo JP, Mahapatra M. International year of millets-2023: Revitalisation of millets towards a sustainable nutritional security. *Technology in Agronomy*. 2023;3(1).
85. Dimkpa CO, Bindraban PS. Nanofertilizers: new products for the industry? *Journal of agricultural and food chemistry*. 2017;66(26):6462-6473.
86. Durán-Lara EF, Valderrama A, Marican A. Natural organic compounds for application in organic farming. *Agriculture*. 2020;10(2):41.
87. FAOSTAT. FAO-Food and agriculture Organization of the United Nations. Rome, Italy: Food and Agriculture Organization of the United Nations; 2022.
88. Kheya SA, Talukder SK, Datta P, Yeasmin S, Rashid MH, Hasan AK, *et al.* Millets: The future crops for the Tropics-Status, challenges and future prospects. *Heliyon*. 2023;9(11).
89. Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *Journal of agricultural and food chemistry*. 2017;66(26):6487-6503.
90. Zhou, Y., Xiao, R., Klammersteiner, T., Kong, X., Yan, B., Mihai, F. C. and Awasthi, M. K. (2022). Recent trends and advances in composting and vermicomposting technologies: A review. *Bioresource Technology*, 360, 127591.