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Subedar Singh

Assistant Professor, Mandsaur
 University, Mandsaur, Madhya
 Pradesh, India

Deepak Kumar

Ph.D. Research Scholar, Department
 of Soil Science and Agricultural
 Chemistry, Acharya Narendra Deva
 University of Agriculture and
 Technology, Ayodhya, Uttar Pradesh,
 India

Ratnalika Maurya

Ph.D. Research Scholar, Department
 of Vegetable Science, Acharya
 Narendra Deva University of
 Agriculture and Technology,
 Ayodhya, Uttar Pradesh, India

Bhawna Saini

Ph.D. Research Scholar, Department
 of Agronomy, Acharya Narendra
 Deva University of Agriculture and
 Technology, Ayodhya, Uttar Pradesh,
 India

Shivendra Kumar Singh

Ph.D. Research Scholar, Department
 of Soil Science and Agricultural
 Chemistry, Acharya Narendra Deva
 University of Agriculture and
 Technology, Ayodhya, Uttar Pradesh,
 India

Vidha Dwivedi

PG Scholar, Department of
 Agronomy, Jawaharlal Nehru Krishi
 Vishwavidyalaya, Rewa, Madhya
 Pradesh, India

Nitin Singh

Ph.D. Research Scholar, Department
 of Agronomy, Acharya Narendra
 Deva University of Agriculture and
 Technology, Ayodhya, Uttar Pradesh,
 India

Mansi Jain

Ph.D. Research Scholar, Department
 of Soil Science and Agricultural
 Chemistry, Acharya Narendra Deva
 University of Agriculture and
 Technology, Ayodhya, Uttar Pradesh,
 India

Corresponding Author: Shivendra Kumar Singh

Ph.D. Research Scholar,
 Department of Soil Science
 and Agricultural
 Chemistry, Acharya
 Narendra Deva University
 of Agriculture and
 Technology, Ayodhya,
 Uttar Pradesh, India

Integrated nutrient management for sustainable crop production: Improving nutrient-use efficiency, soil health and climate resilience

Subedar Singh¹, Deepak Kumar², Ratnalika Maurya³, Bhawna Saini⁴, Shivendra Kumar Singh⁵, Vidha Dwivedi⁶, Nitin Singh⁷, Mansi Jain⁸

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ABSTRACT

Efficient nutrient management is fundamental to sustainable crop production because nutrient availability directly influences crop growth, yield, quality, soil fertility, and resource-use efficiency. Continuous cultivation, imbalanced fertilizer use, declining soil organic matter, nutrient mining, and inefficient fertilizer utilization have created major challenges for sustainable agriculture. Integrated Nutrient Management (INM) offers a holistic approach by combining and complementing mineral fertilizers, organic manures, vermicompost, crop residues, green manures, biofertilizers, and locally available nutrient resources. Organic amendments can improve soil structure, nutrient availability, water retention, microbial activity, and overall soil health (Verma *et al.*, 2024; Singh *et al.*, 2020; Pooja *et al.*, 2022). Field evidence from maize, pigeonpea, mustard, and rice indicates that integrated use of organic and inorganic nutrient sources can improve nutrient uptake and crop productivity (Verma *et al.*, 2018a; Verma *et al.*, 2020; Pradhan *et al.*, 2017; Babu *et al.*, 2017). Balanced management of phosphorus, sulphur, zinc, and boron is also essential for achieving high, sustainable crop productivity (Shukla *et al.*, 2017; Kumar *et al.*, 2018; Shori *et al.*, 2019). Site-specific nutrient management, enhanced-efficiency fertilizers, biofertilizers, precision agriculture, and climate-smart nutrient management can further improve nutrient-use efficiency. This review discusses the major principles, nutrient sources, field evidence, soil-health interactions, precision approaches, climate resilience, and future research priorities for sustainable nutrient management.

Keywords: Integrated nutrient management, nutrient-use efficiency, soil health, vermicompost, organic manure, sulphur, zinc, biofertilizer, precision agriculture, climate-smart agriculture

1. Introduction

Plant nutrients are fundamental determinants of agricultural productivity. Nitrogen (N), phosphorus (P) and potassium (K), together with secondary and micronutrients, regulate photosynthesis, root development, plant growth, reproductive development, grain formation and crop quality. However, fertilizer application beyond crop requirements does not necessarily increase yield and may result in nutrient losses through leaching, runoff, volatilization, fixation and denitrification.

Nutrient management has consequently shifted from simple fertilizer application towards integrated management of nutrient sources, soil fertility and crop demand. Integrated Nutrient Management combines mineral fertilizers with organic manures, crop residues, compost, vermicompost, green manures and biological inputs to maintain productivity while improving soil quality (Wu *et al.*, 2015) [1].

Soil fertility assessment provides an important basis for fertilizer recommendation. Studies on soil fertility status and soil-test-based approaches demonstrate the importance of understanding spatial and temporal variation in nutrient availability before making fertilizer recommendations (Patel *et al.*, 2017; Maneesh *et al.*, 2014) [3, 2]. Thus, sustainable nutrient management should be based on soil testing, crop requirements, nutrient balance, and appropriate timing and placement of fertilizers.

Recent developments in climate-smart agriculture have further expanded the concept of nutrient management towards improving nutrient-use efficiency, soil carbon sequestration and resilience to climate variability (Verma *et al.*, 2026) [4]. Therefore, INM should be considered a component of a broader soil–crop–water–climate management system.

2. Integrated nutrient management and organic nutrient sources

INM is based on the complementary use of different nutrient resources. Mineral fertilizers provide readily available nutrients, while organic sources supply nutrients more gradually and contribute organic matter and biological activity. Their combined use can improve nutrient synchronization and reduce the risk of nutrient losses.

Organic manure application can influence soil physical, chemical and biological properties, including soil structure, water retention, nutrient availability, microbial activity and cation exchange capacity (Verma *et al.*, 2024) [5]. The addition of organic matter can also support nutrient retention and reduce nutrient losses from the root zone.

Field studies have demonstrated the potential of organic formulations combined with fertilizers in pigeonpea. Verma *et al.* (2018a) reported effects of organic formulations and synthetic fertilizer on pigeonpea performance in the eastern region of Uttar Pradesh. Such evidence supports the concept that organic inputs can complement mineral fertilizers rather than necessarily replacing them.

3. Vermicompost and vermiwash in nutrient management

Vermicompost is an important organic amendment produced through the decomposition of organic materials by earthworms. It contains organic matter and plant nutrients and can improve soil aggregation, microbial activity, and nutrient availability.

Singh *et al.* (2020) [6] reviewed the significance of vermicompost for crop and soil productivity and emphasized its potential contribution to sustainable nutrient management. Similarly, Pooja *et al.* (2022) [7] highlighted the beneficial effects of vermicompost on soil and field crops. These findings are supported by broader reviews indicating that vermicompost can improve soil quality and plant growth when applied at suitable rates and under appropriate environmental conditions.

Vermiwash and other liquid organic inputs may provide additional opportunities for nutrient management. Verma *et al.* (2018b) [8] reviewed the significance of vermiwash in crop production, particularly in relation to nutrient availability and biological activity. Such inputs can be incorporated into integrated nutrient programmes where their composition and application practices are properly standardized.

However, vermicompost and vermiwash should be evaluated according to their nutrient composition, maturity, application rate, crop requirement, and soil condition. Their role should therefore be viewed as complementary within an integrated nutrient-management system.

4. Cow urine and organic liquid formulations

Cow urine has been investigated as a locally available biological and nutrient input in organic and natural farming systems. Pradhan *et al.* (2018) [9] reviewed the bio-efficacy of cow urine and described its potential use in crop production, growth-promoting preparations, and biological crop protection. Their review also emphasized the need for further scientific validation of its effects under different crop and environmental conditions.

Field research by Pradhan *et al.* (2017) [10] demonstrated that fertility levels combined with basal and foliar application of cow urine influenced growth and nutrient uptake in Indian mustard. A later study also examined the performance of Indian mustard under fertility levels and cow urine application in the eastern region of Uttar Pradesh (Pradhan *et al.*, 2024) [11].

Organic formulations have also been evaluated with fertilizers in pigeonpea and other crops. Such evidence suggests that organic liquid inputs may be useful supplementary components of integrated nutrient management, particularly when their use is synchronized with crop nutrient requirements.

5. Field evidence of integrated nutrient management

Field experimentation provides the strongest basis for developing practical nutrient-management recommendations. In kharif maize, Verma *et al.* (2020) [12] evaluated different mulching and integrated nutrient-management practices in eastern Uttar Pradesh and demonstrated the importance of combining soil-surface management with nutrient management.

Similarly, Verma *et al.* (2018a) evaluated organic formulations and synthetic fertilizers in pigeonpea and provided evidence for integrating organic inputs with fertilizer management. These studies demon-

strate that nutrient management should be evaluated at the cropping-system level rather than considering individual fertilizer inputs independently.

Research in transplanted rice has also linked nutrient-management technologies with soil biological properties. Babu *et al.* (2017) [13] investigated nutrient-management technologies, soil biomass, and enzymatic activities in transplanted rice under irrigated conditions of the eastern plain zone. The study is particularly relevant because it demonstrates the connection between nutrient management and soil biological functioning.

A further study on basmati rice evaluated NPK levels and biofertilizers and reported their influence on yield and nutrient removal (Singh *et al.*, 2017) [14]. This indicates that fertilizer management and biological nutrient inputs can be integrated to improve nutrient acquisition and crop productivity.

6. Balanced fertilization and nutrient-use efficiency

Nutrient-use efficiency (NUE) is an important indicator of sustainable fertilizer management. It describes how effectively applied nutrients are recovered by crops and converted into useful biomass or economic yield. Improving NUE is particularly important for nitrogen because inefficient N management can lead to ammonia volatilization, nitrate leaching and nitrous oxide emissions (Xu *et al.*, 2012; Chen *et al.*, 2023) [16, 15].

The 4R nutrient stewardship concept—right source, right rate, right time and right place—provides a practical framework for improving fertilizer efficiency (Johnston *et al.*, 2014) [17]. Soil testing, crop-specific fertilizer recommendations, split N application, proper placement and balanced NPK application are therefore essential components of sustainable nutrient management.

Rice research has demonstrated the importance of nutrient scheduling and nutrient-management technologies. Soil-test-crop-response approaches can provide a scientific basis for developing fertilizer recommendations according to soil nutrient supply and crop response (Maneesh *et al.*, 2014; Patel *et al.*, 2017) [2, 3].

7. Phosphorus management

Phosphorus is essential for root growth, energy transfer, flowering and seed development. However, its availability can be strongly influenced by soil chemical properties. Excessive P application can lead to fixation and environmental losses, whereas inadequate P can restrict root growth and productivity (Singh *et al.*, 2025) [18].

Shukla *et al.* (2017) [19] investigated crop geometry and phosphorus levels in chickpea and demonstrated the importance of appropriate P management for crop growth and productivity. Their findings support the use of crop-specific and soil-based phosphorus recommendations. Recent work on phosphorus and irrigation interactions in mungbean further emphasizes that P response can depend on both crop variety and water regime (Pandey *et al.*, 2025) [20]. Thus, nutrient recommendations should increasingly account for interactions among nutrients, genotypes and water availability.

8. Sulphur, zinc and boron management

Secondary and micronutrients are increasingly important in intensive cropping systems because repeated removal of nutrients can create deficiencies even when NPK requirements are adequately supplied.

Sulphur is particularly important for oilseed crops. Kumar *et al.* (2018) [21] studied sulphur and zinc nutrition in rapeseed and demonstrated their importance for growth, yield attributes and yield. Verma *et al.* (2022) [22] reviewed sulphur nutrition in *Brassica* and emphasized its importance for the production potential of oilseed crops.

Zinc deficiency can reduce crop growth, yield and nutritional quality. Agronomic biofortification through zinc application can simultaneously address crop productivity and human nutritional requirements. Pradhan *et al.* (2022) [23] reviewed agronomic zinc biofortification in wheat, providing further support for integrating Zn management with conventional fertilizer practices.

Boron and zinc management are also relevant in maize. *Shori et al. (2019)* [24] reviewed the role of boron, zinc and FYM in maize growth, yield and quality, indicating the importance of micronutrient management in high-yielding maize systems.

Thus, balanced nutrient management should include N, P and K together with S, Zn, B and other micronutrients where deficiencies are identified.

9. Soil health, organic manure and mulching

Nutrient management and soil health are closely interconnected. Organic matter contributes to soil aggregation, water retention, nutrient buffering, microbial activity and carbon storage. *Verma et al. (2024)* [5] emphasized that organic manure can influence physical, chemical and biological soil properties and contribute to soil fertility and sustainability.

Mulching can complement nutrient management by reducing evaporation, moderating soil temperature, suppressing weeds and influencing nutrient cycling. *Bahadur et al. (2018)* [25] reviewed the role of plastic mulch in soil health and crop productivity, while *Verma et al. (2024)* [26] reviewed the effects of mulches on crop, soil and water productivity.

In maize, the combination of mulching and INM was investigated by *Verma et al. (2020)* [12], demonstrating the importance of integrating soil-surface management with nutrient management.

Organic manure can also improve soil water retention and nutrient-holding capacity. Therefore, soil organic matter management should be treated as a long-term component of nutrient management rather than simply an amendment for supplying nutrients.

10. Biofertilizers and biological nutrient management

Biofertilizers contain microorganisms capable of contributing to nutrient availability through nitrogen fixation, phosphate solubilization, potassium mobilization and other rhizosphere processes. Their integration with organic and mineral fertilizers can contribute to sustainable nutrient management.

Singh et al. (2017) [14] reported the response of basmati rice to NPK levels and biofertilizers, indicating the potential of biological nutrient inputs in rice production. More broadly, biofertilizers can contribute to nutrient cycling and may reduce dependence on external nutrient inputs under suitable soil and crop conditions.

However, biofertilizer performance is influenced by microbial strain, inoculum quality, soil pH, temperature, moisture, crop genotype and fertilizer management. Therefore, quality control and location-specific recommendations are essential.

11. Soil fertility assessment and site-specific nutrient management

Uniform fertilizer recommendations may not adequately reflect the spatial variability of soil fertility. Soil-test-based nutrient management provides a more scientific basis for fertilizer recommendations.

Patel et al. (2017) [3] documented soil fertility status in Jaunpur district of eastern Uttar Pradesh, demonstrating the importance of regional soil-fertility assessment. Soil-test-crop-response approaches provide an additional framework for linking soil nutrient availability with crop response (*Maneesh et al., 2014*) [2].

Site-specific nutrient management can be strengthened through GPS, GIS, remote sensing, soil sensors, yield mapping and digital decision-support systems. Such approaches allow fertilizer application to be adjusted according to spatial variability and crop demand (*Baishya et al., 2021*; *Ali et al., 2024*) [28, 27].

12. Precision agriculture and enhanced-efficiency fertilizers

Precision agriculture offers opportunities to improve fertilizer-use efficiency by applying nutrients at appropriate rates and locations. Remote sensing, drones, sensors and digital platforms can assist in identifying crop variability and nutrient stress.

Enhanced-efficiency fertilizers, including controlled-release and stabilized nitrogen fertilizers, can reduce nutrient losses by synchronizing nutrient release with crop demand (*Dimkpa et al., 2020*) [29]. Their effectiveness depends on crop duration, soil characteristics, weather conditions and management practices.

Precision nutrient management should not, however, be restricted to expensive technologies. Soil testing, nutrient budgeting, crop monitoring and field-specific fertilizer scheduling can provide relatively low-cost approaches for improving nutrient-use efficiency.

13. Nutrient management under climate change

Climate change affects nutrient cycling through changes in temperature, rainfall, soil moisture, crop growth and microbial activity. Drought, heat, salinity and excessive rainfall can alter nutrient availability and uptake.

Verma et al. (2024) [5] highlighted the broader implications of climate change for agricultural production, while *Verma et al. (2026)* [4] specifically addressed climate-smart nutrient management, sustainable crop production and soil carbon sequestration. Climate-smart nutrient management therefore needs to integrate nutrient-use efficiency, soil carbon management and resilience to climatic stresses.

Salinity is another important constraint. *Verma et al. (2018c)* [30] evaluated the responses of ber varieties to different levels of salinity and demonstrated the effects of salinity on plant performance and nutrient-related processes. Under such conditions, nutrient management should be integrated with salt-tolerant varieties, appropriate irrigation, soil amendments and improved soil-water management.

14. Nutrient management, carbon sequestration and sustainability

Long-term nutrient management should consider both crop productivity and soil carbon. Organic manure, crop residues, compost and reduced soil disturbance can contribute to carbon retention while improving soil structure and nutrient cycling.

Integrated nutrient management can therefore contribute to multiple sustainability outcomes: increased nutrient-use efficiency, improved soil organic matter, enhanced microbial activity, greater water-use efficiency and reduced nutrient losses.

The climate-smart nutrient-management framework proposed by *Verma et al. (2026)* [4] is particularly relevant because it links nutrient management with soil carbon sequestration and climate resilience. Such integration represents an important future direction for sustainable intensification.

15. Emerging research priorities

Future nutrient-management research should focus on:

1. Soil-test-based and crop-specific nutrient recommendations.
2. Integration of organic and inorganic nutrient sources.
3. Standardization of vermicompost, vermiwash and other organic inputs.
4. Improved nutrient synchronization through split and precision applications.
5. Integrated management of N, P, K, S, Zn and B.
6. Biofertilizer integration with mineral and organic fertilizers.
7. Nutrient management under drought, salinity, heat and excessive rainfall.
8. Development of climate-smart fertilizer strategies.
9. Long-term evaluation of soil organic carbon and nutrient balances.
10. Low-cost digital and precision nutrient-management technologies.
11. Integration of nutrient management with water and residue management.
12. Development of farmer-friendly decision-support systems.

16. Conclusion

Integrated Nutrient Management provides a practical framework for sustainable crop production by combining mineral fertilizers, organic manures, vermicompost, biological inputs and site-specific nutrient-management approaches. Evidence from the literature demonstrates that organic amendments can improve soil properties, while integrated use of organic and inorganic sources can improve crop productivity and nutrient uptake.

The studies of Verma and collaborators provide valuable evidence across multiple dimensions of nutrient management, including vermicompost, vermiwash, organic manure, cow urine, phosphorus, sulphur, zinc, boron, biofertilizers, mulching, soil fertility, rice nutrient management and climate-smart nutrient management. These studies collectively support a systems approach to nutrient management rather than an isolated fertilizer-centric approach.

Future nutrient management should move towards balanced, integrated, site-specific, resource-efficient and climate-smart nutrient stewardship. Soil testing, organic-resource recycling, balanced fertilization, biological inputs, precision technologies and improved fertilizer formulations should be combined according to crop, soil and climatic conditions. Such an approach can simultaneously support crop productivity, soil health, nutrient-use efficiency, economic sustainability and environmental quality.

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