A Review on Sustainable Crop Production through Integrated Nutrient Management Using Nano-Fertilizers and Organic Inputs

Rajanikant [1], Naveen Kumar [2], Dr. Binod Kumar Pandey [3], Dr. Srinivasa Rao Meesala [4*]
[1] Postgraduate Student, School of Agriculture Sciences, K.K. University, Bihar Sharif, Nalanda, Bihar 803115, India
[2] Ph.D. Research Scholar, School of Agriculture Sciences, K.K. University, Bihar Sharif, Nalanda, Bihar 803115, India
[3] Associate Professor, School of Agriculture Sciences, K.K. University, Bihar Sharif, Nalanda, Bihar 803115, India
[4] Professor and Dean, School of Agriculture Sciences, K.K. University, Bihar Sharif, Nalanda, Bihar 803115, India

* Corresponding Author: **Dr. Srinivasa Rao Meesala**

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Abstract
In order to ensure that the objective of feeding the ever-growing world population is fulfilled, crop production must be efficient and sustainable. It is important that crops preserve the soil quality and protect the environment. INM (Integrated Nutrient Management) is an interesting approach, which involves the use of chemical fertilizers, organic manure, and nanotechnology. For example, the combination of chemical fertilizers with the organic fertilizers like farmyard manure, compost, and green manure leads to better soil conditions, improves microbial activities, and helps to retain water and nutrients. Also, they help to improve soil fertility and sequester carbon. The application of nano-fertilizers can be viewed as the most recent innovation in agriculture nutrient management due to its capacity to provide nutrients effectively and efficiently. Due to the smaller particle sizes, larger surface area, and higher nutrient uptake, nano-fertilizers allow plants to absorb nutrients more easily. As a result, there will be a decrease in the loss of nutrients due to leaching, volatilization, and runoff. However, their large-scale adoption is constrained by challenges such as high production costs, limited field-scale validation, regulatory uncertainties, and concerns regarding the long-term environmental and ecological impacts of nanomaterials. The integration of organic and nano-based inputs within an INM framework provides a balanced and efficient nutrient supply that addresses current crop nutritional requirements while supporting the long-term sustainability of agricultural production. Future research should focus on developing cost-effective nano-fertilizers, establishing standardized regulatory frameworks, and conducting long-term field studies to ensure their safe, practical, and sustainable adoption in modern agriculture.

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1. Introduction

Currently, among all the problems that humans face, one of the most important ones is that of sustainable management of natural resources like soil and water while raising agricultural productivity as well as protecting the environment. With the increase in population of the world, these problems get increasingly difficult to solve. Hence, it is extremely important to maintain a good balance between food production, soil health, and environment for ensuring food and nutrition security of the country. In India itself, the level of grain production has increased from 52 million tonnes in 1951-52 to a record high of 348 million tonnes in 2025-26 (expected) due to efficient utilization of nutrients.

But the problem of inefficient utilization of these nutrients in form of excess or imbalanced fertilizers has led to decreased nutrient-use efficiency. Moreover, humans are also under threat and the rate of climate change is accelerating. Previously, the practice of nutrient management was simply concerned with maximizing the yield of crop, but now sustainable nutrient management is concerned with maximizing productivity while maintaining soil quality and reducing loss of nutrients from leaching and runoff. Nutrition is vital in ensuring that there is continuous provision of good quality and quantity of agricultural production. But the use of fertilizers is important in order to ensure that the necessary nutrients are available to crops. Prolonged usage of fertilizers can have detrimental effects on the ecosystem. Ecological issues like biomagnification, eutrophication, nitrate buildup, soil salination, heavy metals accumulation and greenhouse effect are some of the negative impacts linked to excess fertilizer use. The excess use of chemical fertilizers has resulted in numerous problems which are interconnected, namely pollution of soil, water and air. These limitations of conventional fertilizer-based nutrient management have highlighted the need for integrated and sustainable approaches that enhance nutrient use efficiency while reducing environmental degradation. Consequently, Integrated Nutrient Management (INM), which combines chemical fertilizers with organic nutrient sources and emerging technologies such as nano-fertilizers, has gained increasing attention as an effective strategy for achieving sustainable crop production and maintaining long-term soil health. Integrated Nutrient Management (INM) is an integrative process which aids in ensuring long-term sustainable agriculture and food security by reducing pollution and improving soil health through physical, chemical, and biological improvement of the soil. INM is a method that ensures enhanced plant growth and optimized resource utilization together with environmental protection and quality maintenance. The implementation of advanced INM methods in a thoughtless way can bring about reduction in dependence on the use of chemical fertilizers, as well as decrease the cost of production for the farmers and the environment while leaving the yield of the crops untouched. Nanotechnology is a wonderful invention of mankind and has been contributing towards advancement in various economic sectors. Nanoparticles possess the capability to transport various kinds of nutrients and can be engineered in such a way that nutrient release can take place slowly and gradually in accordance with the needs of the plants with minimum negative impact. High-quality manures with good levels of nutrients are urban compost, farmyard manure (FYM), crop residues, municipal wastes, rural compost, sewage sludge, vermicompost, biologs, and various other agricultural industrial by-products. Compost and FYM used to be the primary sources for keeping soils fertile and stable crop production in the past. Apart from these, non-consumable oilcakes and food processing waste can also act as sources of organic nutrients (Sharma *et al*. 2022) [8].

2. Integrated Nutrient Management (Inm)

Integrated Nutrient Management (INM) is a whole approach that seeks to improve the efficiency of fertilizer use, ensure soil fertility and increase its productivity. The practice offers a holistic way of providing macro- and micro-nutrients to plants and also ensuring the best soil conditions, physically, chemically, and biologically. INM also helps protect the environment from over-reliance on chemicals in the form of fertilizers. Apart from that, INM also helps maintain long-term soil nutrient balance and proper waste disposal and recycling in agriculture. Integrated Nutrient Supply Utilization/Management (INM) involves the efficient and sustainable use of all sources of plant nutrients. INM stresses the joint use of chemical fertilizers along with other sources of organic materials like animal manure, composts, and green manure. Research indicates that the combined use of chemical fertilizers with organic materials produces better yields compared to the separate use of any of the sources of nutrients (Bhattacharyya *et al*., 2012). The following sections summarize the major objectives and advantages of Integrated Nutrient Management, highlighting its contribution to sustainable crop production, soil health, environmental protection, and farm profitability.

2.1. Objective of INM

- To optimize the efficient use of nutrient resources within a cropping system or crop rotation structure.
- To integrate both natural and man-made soil nutrient reserves for crop production purposes.
- To conserve soil fertility and productivity for the future.
- To increase synergism among different organisms of the soil ecosystem for better results.
- To limit the negative effects of the irrational use of chemical fertilizers on the environment.
- To obtain sustainable yield over a long period of time with very little impact on native soil fertility.
- To inform farmers about eco-friendly methods of producing contaminant-free food.
- To provide suitable and long-term economic profitability.

2.2. Advantage of INM

The adoption of INM offers multiple agronomic, environmental, and economic benefits. These advantages are discussed under the following subheadings.

2.2.1. Increased Fertilizer Utilization Efficiency

INM promotes the balanced and rational application of nutrients sources such as organic manure, inorganic fertilizer, and biological fertilizer. Research has demonstrated that the application of INM practices results in the marked improvement of efficiency of fertilizer through the supply of nutrients to the crops in adequate amounts and at suitable stages of growth according to their requirements (Kumar *et al*. 2016; Islam *et al*. 2019) [6, 4]. This in turn leads to the reduced nutrient loss and efficient nutrient acquisition by crops.

2.2.2. Enhanced Soil Fertility and Health

INM promotes the use of organic manures and bio-fertilizers to improve soil fertility and health. Application of organic manures increases soil organic matter while improving nutrient retention, soil structure, and moisture-holding capacity (Kumar *et al*. 2016; Islam *et al*. 2019) [6, 4]. Likewise, nitrogen-fixing bacteria and mycorrhizal fungi facilitate nutrient availability and uptake, thereby enhancing soil fertility (Goswami *et al*. 2016) [3].

2.2.3. Sustainable Crop Production

INM ensures that crops are provided with a balanced and sustained flow of nutrients, leading to sustainable production of crops in the long run. Research has shown that INM produces greater yields when compared to traditional nutrient management strategies (Islam *et al*. 2020) [5]. This is because both inorganic and organic nutrients are used in INM, ensuring the provision of nutrients at various stages of plant development.

2.2.4. Environmental Benefits

INM contributes to environmental protection by minimizing nutrient losses and reducing the risk of soil and water pollution. Soil test-based nutrient management and balanced fertilizer application prevent excessive use of chemical fertilizers, thereby reducing nutrient runoff and leaching (Islam *et al*. 2020) [5]. Furthermore, integrating organic manures and bio-fertilizers with chemical fertilizers decreases reliance on synthetic fertilizers and promotes a more sustainable agricultural production system (Kumar *et al*. 2016; Goswami *et al*. 2016) [6, 3].

2.2.5. Economic Viability

Farmers have recognized that INM practices are not only economically feasible but also financially rewarding. Studies indicate that INM enhances profitability by reducing input costs and increasing returns on investment (Kumar *et al*. 2016) [6]. Higher crop yields combined with the efficient utilization of diverse nutrient sources ultimately improve farmers' economic outcomes.

3. Nano-Fertilizers

Nano-fertilizers (NF) are nano materials (nm) which differ markedly from their bulk form materials.NF technology is highly innovative using physical, chemical, and biological approaches for formulation. The use of nano-fertilizers in agriculture has enabled a precise and targeted nutrient delivery approach resulting in fostering sustainability and accuracy in drug delivery. Nutrient fertilizers (NF) are one of the major factors for production of crops. They are either conventional fertilizers or bulk materials processed to Nano (scale of 1-100 nm). Nano-fertilizers are more efficient than traditional fertilizers as far as their nutrient uptake efficiency is concerned. The reason is that nano-fertilizers offer efficient and selective release of nutrients along with high surface areas and better uptake efficiency of nutrients by crops. Thus, they prevent any losses of nutrients through leaching, volatilization, and runoffs without polluting the environment; hence, making fertilizer use more efficient and productive. Traditional fertilizers on the other hand need high application doses and have low nutrient uptake efficiency.

3.1. Types of Nano-Fertilizers

3.1.1. Based on Action

3.1.1.1. Controlled-Release Nano-Fertilizers

Nanoparticles are used in these fertilizers to control nutrient release, thereby enhancing nutrient uptake and limiting environmental pollution (Derosa *et al*. 2010) [11]. Controlled-release nano-fertilizers encase nutrients with nano-sized carrier materials composed of polymers, lipids, or inorganics (Liu *et al*. 2015) [10]. Nutrient release from such carriers can be influenced by environment factors such as temperature, pH and moisture or by stimuli-responsive mechanisms such as biodegradation or enzyme-mediated degradation (Ghormade *et al*. 2011) [12].

3.1.1.2. Targeted Delivery

Significant movement mostly in soil molecules designed to transport nutrients or the like compounds directly to the plant are called targeted delivery. While it comes to targeted specific molecules in the soil, they are tiny molecules that can bind to plant hormones and enzymes and deliver them in an effective and efficient manner to the plant.

3.1.1.3. Plant Growth-Stimulating Nano-Fertilizers

Some nano-fertilizers, like carbon Nanotubes (CNTs), stimulate plant growth by interacting with roots and increasing the production of hormones. They also raise the levels of carbon and other nutrients in the soil. CNTs are characterized by rolled-up sheets of carbon atoms and have unique properties that make them excellent fertilizers. CNTs have the ability to adsorb and release nutrients, can improve soil structure, increase water retention, and contribute to plant growth (Mondal *et al*. 2011) [13].

3.1.1.4. Water and Nutrient Loss-Controlling Fertilizers

Nano-fertilizers possess nanoparticles that have the capability of controlling the rate of release of fertilizers into the soil, thus allowing farmers to make use of a smaller quantity of fertilizer while at the same time achieving the same level of production. Different methods of designing nano-fertilizers that can control nutrient release and reduce water loss are being studied (Okey *et al*. 2021) [14].

3.1.2. Based on Nutrient

3.1.2.1. Inorganic Nano-Fertilizers

Inorganic nano-fertilizers are metal, metalloid, and non-metallic nanoparticles which can deliver nutrient elements like nitrogen, phosphorous, potassium required in large quantities by plants. These fertilizers have been designed to improve the nutrient absorption efficiency of plants and can be used to increase agricultural productivity (Krishnani *et al*. 2022 And Kalia *et al*. 2019) [15, 16].

3.1.2.2. Organic Nano-Fertilizers

The nanoparticles that form organic nano-fertilizers are generated from organic materials and are intended to slowly deliver nutrients to the soil. They are non-toxic, biodegradable, and made from natural sources; they can also help hold moisture and change pH so that plants can more easily absorb the nutrients that they need (Fatima *et al*. 2021) [17].

3.1.2.3. Hybrid Nano-Fertilizers

Hybrid nano-fertilizers combine traditional fertilizers and nanotechnology-based fertilizers to provide both a slow and a sustained release of nutrients as well as improved nutrient utilization (Tarafder *et al*. 2020) [18]. These nano-fertilizers ameliorate fertilizer efficiency and also limit the environmental impact that is coupled with the production and application of fertilizers (Kah *et al*. 2013) [19].

3.1.3. Based on Consistency

3.1.3.1. Surface-Coated Nano-Fertilizers

Surface-coated nano-fertilizers are composed of nanoparticles (NPs) made from silica, iron, and other nutrient-rich materials, which include traditional fertilizers with nano-scale additives, nano-scale coatings, and fertilizers coated with nano-scale substances (Solanki *et al*. 2015) [20]. It leads to an increase of fertilizer absorption rate, thereby improving its utilization efficiency and eliciting better growth of plants.

3.1.3.2. Synthetic Polymer-Coated

Scientists have engineered synthetic polymer-coated nano-fertilizers that have a thin layer of synthetic polymer. This coating is meant to protect the nano-fertilizers against environmental degradation and also enhance their handling characteristics (Tyagi *et al*. 2022 And Badran *et al*. 2016) [21, 22]. Furthermore, it ensures that the nano-fertilizers are consistently dispersed in the soil, which allows for even and more efficient nutrient delivery to plants.

3.1.3.3. Biological Product-Coated

3.1.3.1. Organic Compound-Coated

Biological product- coated nano-fertilizers, for example, humic acid and nanoparticles (NPs), help enhance the fertility of soil by improving the retention of water as well as stimulating the activity of beneficial microbes. Furthermore, nano-fertilizers, which are coated with plant growth regulators allow the plant to supply essential nutrients while managing its growth and development.

3.1.3.2. Microbe-Coated Nano-Biofertilizers

Nano-biofertilizers is the combination of NPs with beneficial soil microorganisms that improve the availability, uptake, and efficiency of plant nutrients. The small size and large surface area of NPs facilitate the effective transport of nutrients to plant roots and tissues, and the microorganisms are involved in nutriment solubilization, mineralization, and nitrogen fixation (Kottegoda *et al*. 2011) [23].

Some real-world examples of usage of nano-fertilizers in various cropping systems can be presented to further illustrate the potential of nano-fertilizers in sustainable agriculture. For cereal crops like rice and wheat, nano-nitrogen fertilizers have been found to increase the nitrogen utilization efficiency of plants without compromising or even increasing the grain yields while using lesser amounts of nitrogen fertilizers (Verma *et al*., 2022; Mim *et al*., 2025) [31, 33]. For maize, nano-zinc fertilizers have been found to improve zinc accumulation, growth of plants, and quality of grains owing to better nutrient utilization (Verma *et al*., 2022; Gangwar *et al*., 2023) [31, 32]. In the case of horticultural crops like tomato and cucumber, the foliar application of nano-fertilizers has been found to result in increased nutrient absorption, fruit yields, and fruit quality along with decreased losses of nutrients and requirement of fertilizer use (Gangwar *et al*., 2023; Mim *et al*., 2025) [32, 33]. Similarly, for pulse and oilseed crops, nano-fertilizers have been found to exhibit positive impacts through nutrient utilization, physiological performance, and increased productivity.

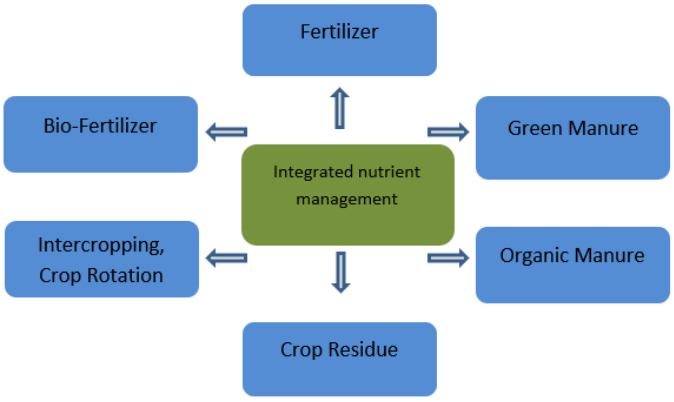

Fig 1: Representing the applications of Integrated Nutrient management

3.2. Features That Make Nfs Effective In Improving Nue And Reducing Nutrient Losses

One of the main properties of NFs is that they can be absorbed by plants whether they are applied foliarly or as soil amendments because of their very small particle size (<100 nm) (Liscano *et al*. 2000) [24]. Through possessing a very large surface area, NFs can bring about a very high reactivity which not only increases nutrient availability but also raises plant nutrient use efficiency (Liscano *et al*. 2000 And Siddiqi *et al*. 2017) [24, 25]. In addition, NFs are water-soluble, which enables the spread of nutrients in the soil and their further uptake by plants. To increase their absorption, availability to plants, and reduce their bulk requirements, fertilizers are put into NPs (Chhipa *et al*. 2017) [26]. For example, nutrient provision to plants can be maintained at an even level during their development phase through the use of zeolite-based NFs. Also, the slow and targeted release (Singh *et al*. 2017) [27] of NFs (Siddiqi *et al*. 2017) [25] lower their toxicity to plants (Sohair *et al*. 2018) [28] and reduce nitrogen losses due to volatilization, leaching, fixation, denitrification as well as salt accumulation in soil.

4. Organic Fertilizers and Its Types

4.1. Farmyard Manure (FYM)

Farmyard manure continues to be a vital organic fertilizer in India. It is prepared mainly by decomposing solid and liquid excrements of animals mixed with litter and leftover feed. Apart from providing the essential nutrients for plants, farmyard manure is an excellent source of organic matter, which stimulates the microbial life in the soil. Well-decomposed farmyard manure normally contains about 0.5% nitrogen (N), 0.2% phosphorus pentoxide (P2O5), and 0.5% potassium oxide (K2O).

4.1.2. Compost

Composting is a way of working with nature to recycle organic and biodegradable food waste into a form of organic matter that is stable and can be used as a fertilizer and/or a soil amendment in agriculture (Wolka *et al*. 2015) [29]. The quality and composition of compost depend on the nature of raw materials used, composting process, conditions during decomposition, and addition of nutrients in the course of composting. Converting food and municipal solid waste into compost for high yield and soil health can manage soil organic matter and reduce carbon footprint (Razza *et al*. 2018) [30].

4.1.3. Vermi-Compost

Vermi-compost, also called worm compost is a valuable soil conditioner prepared from the decomposition of organic wastes by earthworms and microbes working together. This type of compost is similar to humus and contains both macro and micronutrients.

4.1.4. Green Manure

Green manures are fresh and un-decomposed plant materials used as organic fertilisers. Green manuring not only improves soil structure but also helps in the control of soil erosion. In fact, there are two methods: the first method is growing the leguminous in the field and, after they have matured and flowered, they are incorporated into the soil. These plants include dhaincha, sunhemp, clusterbean, and various other species of sesbania. The practice of green leaf manuring involves the incorporation into the soil of such parts (leaves and twigs) as are collected from off-site trees and shrubs which are then supplied to the land for green leaf manuring. Some of the species used for green leaf manure include neem, mahua, subabul, karanj, and wild indigo.

5. Integrated Nutrient Management Utilizing Nano-Fertilizer and Organic Fertilizer

Integrated Nutrient Management (INM) is capable of efficiently improving plant productivity and resource use optimization, at the same time, environment safety and resource quality are well taken care of. Crop production can be accelerated up to 8-150% over conventional methods by INM and further it helps in water-use efficiency, profits, grain quality, soil health, and sustainability for the farmers. INM is a holistic approach to supply, use, and management of nutrients and integrates all the essential nutrients to plants. Chemical fertilizers, animal manures, compost, and green manures are carefully applied in this combination.

6. Challenges and Future Prospects

However, despite the advantages they offer, there are some issues that make it difficult to apply nano-fertilizers widely in INM technology. First, the expensive nature and lack of availability of the nano-fertilizer hinders its wide application, especially among small-scale farmers. Inadequate information on the effect of nanoparticles on the soil ecosystem and food safety calls for further research. There are no standardized protocols for the use of nano-fertilizers in terms of rate, mode of application, and regulations. In addition, there is need for proper farmer education in order to implement the INM technology successfully. The coupling of nano-fertilizers with organic and chemical fertilizers using the principles of Integrated Nutrient Management (INM) presents huge potential for sustainable agriculture. Future research should be centered on the development of crop-specific and location-specific nano-fertilizer formulations for efficient nutrient utilization and increased productivity. Nanotechnology could play a critical role in achieving a precise and selective nutrient delivery system which would lead to lower levels of fertilizer application and reduced environmental pollution. Furthermore, integration of nano-fertilizers with other modern agriculture technologies like precision agriculture and digital agriculture would provide more scope to improve nutrient management techniques.

7. Conclusion

Integrated nutrient management (INM) practices that use nano-fertilizers combined with organic fertilizers are a highly efficient, sustainable, and environmentally friendly approach to nutrient management. The combination results in higher nutrient use efficiency, improved soil fertility, and enhanced crop yield and growth. Organic inputs help maintain long-term soil health, while nano-fertilizers enable precise nutrient delivery with minimal nutrient losses. Together, they reduce

the environmental risks associated with excessive chemical fertilization. Hence, the integration of INM with nano- and organic fertilizers is the need of the hour to achieve sustainable agricultural production, improve soil quality, and ensure continuous and adequate food supply for a growing population. Future research needs to be concerned with large-scale, multisite field trials of nano-fertilizers to assess their agronomic efficacy and environmental safety over time. Additionally, creation of standard frameworks for regulation, guidelines on biosafety, and inexpensive technologies for production is also critical to promote their usage. Fulfillment of these research and policy challenges will pave the way for greater contribution of nano-based INM to sustainable agriculture.

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Author's Contribution

Rajanikant and NK collected the review of literature, conceptualized and prepared the manuscript as part of research work under the supervision of SRM and BKP. SRM guided the overall structure, provided critical reviews and supervised the review process.

Compliance with ethical standards

Conflict of Interest: The authors assure and clarify that there are no known conflicts of interest occurs which could influence the research pointed in this review. This work has been presented and conducted independently without financial or personal relationships that could be perceived as biasing the content.

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