PLANT SCIENCE TODAY
Vol 13(sp1): 1-10
https://doi.org/10.14719/pst.11099

eISSN 2348-1900

REVIEW ARTICLE

Nano-enabled precision nutrition: A breakthrough strategy for high-efficiency crop nutrition and soil restoration

Shreya Singh[1], Shanti Kumar Sharma[2], B Sri Sai Siddartha Naik[3*], Kamalakar Jogula[4], Anurag Bera[5], Bairi Raju[4], Ch. Ramesh[3], Aishwarya Sharma[6], Bollaveni Sathish Kumar[7], Saha Priyanka[8], J Narendar[3], A Sathish[3], Tadela Susmitha[9], P Gurumurthy[10], Jitendra Singh Bamboriya[11], Kayitha Vilakar[12], Devika A R[13] & Adarsh Sharma[14]

[1]Department of Soil Science and Agricultural Chemistry, Udai Pratap College (Autonomous), Bhojubir 221 002, Varanasi, Uttar Pradesh
[2]Human Resource Management Unit, ICAR-Krishi Bhavan, New Delhi 110 001, India
[3]Department of Agronomy, Agriculture College, Professor Jayashankar Telangana Agricultural University, Warangal 506 006, Telangana, India
[4]Department of Soil Science, Agricultural College, Professor Jayashankar Telangana Agricultural University, Warangal 506 006, Telangana, India
[5]North Bengal Regional Research and development and D Centre, Tea Research Association, Nagrakata, Jalpaiguri 735 225, West Bengal, India
[6]Department of Zoology, Abhilashi University, Mandi 175 028, Himachal Pradesh, India
[7]Agriculture college, Professor Jayashankar Telangana Agricultural University, Jagtial 505 529, Telangana, India
[8]ICAR-Krishi Vigyan Kendra, West Garo Hills, ICAR Research Complex for North Eastern Hill Region, Umiam 793 103, Meghalaya, India
[9]School of Agricultural Sciences, Malla Reddy University, Hyderabad 500 100, Telangana, India
[10]Department of Soil Science and Agricultural Chemistry, Agriculture College, Acharya N. G. Ranga Agricultural University, Naira 532 185, Andhra Pradesh, India
[11]College of Agriculture, Agriculture University, Sumerpur 306 902, Rajasthan, India
[12]Department of Soil Science and Agricultural Chemistry, B J R Agricultural College, Professor Jayashankar Telangana Agricultural University, Jillella 505 405, Telangana, India
[13]Department of Agricultural Biochemistry, School of Agricultural Sciences, Malla Reddy University, Hyderabad 500 100, Telangana, India
[14]Directorate of Extension Education, Maharana Pratap University of Agriculture and Technology, Udaipur 313 001, Rajasthan, India

*Correspondence email - siddunaik08@gmail.com

Received: 04 August 2025; Accepted: 04 January 2026; Available online: Version 1.0: 06 March 2026

Cite this article: Shreya S, Shanti KS, Sri SSNB, Kamalakar J, Anurag B, Bairi R, Ramesh C, Aishwarya S, Bollaveni SK, Saha P, Narendar J, Sathish A, Tadela S, Gurumurthy P, Jitendra SB, Kayitha V, Devika AR, Adarsh S. Nano-enabled precision nutrition: A breakthrough strategy for high-efficiency crop nutrition and soil restoration. Plant Science Today. 2026; 13(sp1): 1-10. https://doi.org/10.14719/pst.11099

Abstract

Population growth, climate change and resource limitations pose significant challenges to the global agriculture sector and new strategies are required to ensure sustainable food production. Nanotechnology has emerged as a promising approach, particularly in those related to soil health and nutrient management. Traditional fertilizers encourage nutrient runoff, leaching and soil deterioration, which negatively impact the environment and the economy. Utilizing the special qualities of nanoparticles, nanostructures, nano-fertilizers and nano-carriers produced groundbreaking solutions, as small particles improve solubility, focus nutrient delivery and allow controlled release mechanisms, all of which increase nutrient absorption efficiency while reducing environmental impact. Use of nanotechnology in agriculture has generated a lot of attention because of its potential to improve agricultural yield and soil fertility. Chitosan-based nano-fertilizers and other nano-enabled soil additives have the potential to improve the soils' structure and water-retention ability, which supports the adoption of sustainable agriculture. Nanotechnology offers revolutionary solutions for water shortages, soil deterioration and soil management, along with benefits. However, widespread adoption of nanotechnology in agriculture remains difficult. Ineffective nutrient delivery is caused by variations in soil properties, moisture content and agro-ecological conditions. Recent research and development efforts have been made to promote better, more dependable, environmentally friendly and sustainable farming practices, which might be promoted by integrating nanotechnology into agricultural practices.

Keywords: crop health; nano-fertilizers; precision nutrition; soil amendments; sustainable agriculture

Introduction

Modern crop production is increasingly restricted by means of declining soil fertility, climatic stresses and the inherent complexity of plant nutrient absorption (1, 2). While foliar application contributes minimally, plant roots stay the primary interface for nutrient acquisition, ruled by way of root structure, soil chemical gradients and a network of especially particular membrane-specific transporters including NRT1/NRT2 (nitrate), AMT (ammonium) and PHT (phosphate). Uptake is pushed by provider-mediated delivery and ATPase-structured ion pumps, regulated by way of electrochemical gradients, hormonal signaling and rhizosphere interactions (3). These structures detect kinetic boundaries-transporter saturation, ion competition and pH/redox-dependent availability-which together determine nutrient uptake performance and inner distribution to shoots and reproductive organs (4).

While in precision nutrition, traditional fertilizer practices are constrained by several interconnected constraints. Nutrient-use efficiency (NUE) remains extremely low, often underneath 50 % for nitrogen and 20 % for phosphorus, resulting in big nutrient losses through leaching, volatilization and eutrophication (5). Root transport systems are inherently non-specific, permitting not only the simplest vital ions but also poisonous solutes to accumulate under imbalanced nutrient situations. Furthermore, laboratory findings often fail to translate to subject realities because soil–climate–microbial interactions dynamically adjust nutrient bioavailability in methods managed experiments can't size (6). Nutrient uptake is also constrained through transporter kinetic limitations, wherein ions, along with ammonium and potassium, compete for the same shipping pathways, reducing average absorption charges. Collectively, those demanding situations exhibit that nutrient absorption relies not merely upon the quantity of fertilizer applied but on the interaction among rhizosphere chemistry, root transporter behavior and the physiological nutrient demand of the plant (7).

Nanotechnology has emerged as a promising solution to overcome inefficiencies in conventional fertilizer use, with the latest research consisting of the software of silica nanoparticles synthesized from coir pith through acidic sol-gel techniques showing enhanced germination and progressed enter economics (8). Nano-fertilizers provide controlled and slow-release nutrient transport, more solubility and root uptake, reduced nutrient losses and an improvement in nutrient use efficiency (NUE) by 30–40 %, while also reducing ordinary fertilizer utility costs. This advance constitutes a widespread leap forward in precision agriculture, aligning environmental sustainability with economic feasibility and paving the way for greater efficiency and eco-friendly farming practices (9). Innovative soil amendments, which encompass biochar, play an essential role in advancing nutrient control techniques by influencing microbial processes within the soil without delay. Molecular analyses have demonstrated that biochar can modulate denitrifier gene expression, improving N_2O reductase activity and thereby extensively reducing greenhouse gas emissions even as it concurrently improves nitrogen retention (10). These biochar-microbe-soil interactions are vital for minimizing fertilizer dependency and ensuring extra sustainable nutrient cycling throughout numerous agro-ecosystems. However, technological viability in agriculture can't be assessed solely on environmental overall performance; economic profitability remains equally essential. Investment research spotlights that industries able to gain investor self-assurance should exhibit resilience, scalability and predictable returns. Consequently, fertilizer improvements, along with nano-fertilizers and soil amendments, have to be evaluated through an economic lens that considers manufacturing costs, farmer profitability, market enlargement and standard funding splendor (11). This dual emphasis on environmental and financial sustainability ensures that emerging technologies are not only the most effective and ecologically sound but also financially possible, thereby facilitating their adoption at scale inside modern agricultural structures.

Fig. 1 illustrates the complex fate of fertilizer application in agricultural fields, showing that only a fraction of the applied nutrients is taken up by plants while the reminder is lost through various pathways. Nutrients may leach into deeper soil layers, run off with surface water, or volatilize into the atmosphere, particularly in the case of nitrogen fertilizers. Additionally, processes such as nitrification, denitrification and microbial transformations further reduce nutrient availability. Phosphorus and potassium often become fixed in soil colloids, limiting their immediate uptake (12). Overall, the figure emphasizes the inherent inefficiency of conventional fertilizer practices and underscores the need for improved nutrient delivery approaches, including nano-enabled technologies.

This evaluation assesses the speculation that precision vitamins supported by nano-fertilisers and soil amendments can considerably enhance nutrient-use efficiency and crop productivity, but substantial adoption calls for proof of both environmental advantages and financial profitability (13). Addressing this hypothesis is pressing inside the global environmental–financial nexus, wherein decreasing nutrient losses, increasing yields and decreasing prices must converge to ensure sustainable crop production.

Methodology

The substances and methods involved a scientific literature review of the use of databases such as Scopus and Web of Science, applying keywords related to nano-fertilizers, precision nutrients and biochar amendments. Data extraction focused on nutrient uptake performance, microbial interactions and economic parameters, permitting reproducible synthesis of findings and simplified cloth-strength drift analysis for feasibility.

Nano-fertilizers: Basics and their types

Plants may absorb nanoparticles included in nano-fertilizers, which

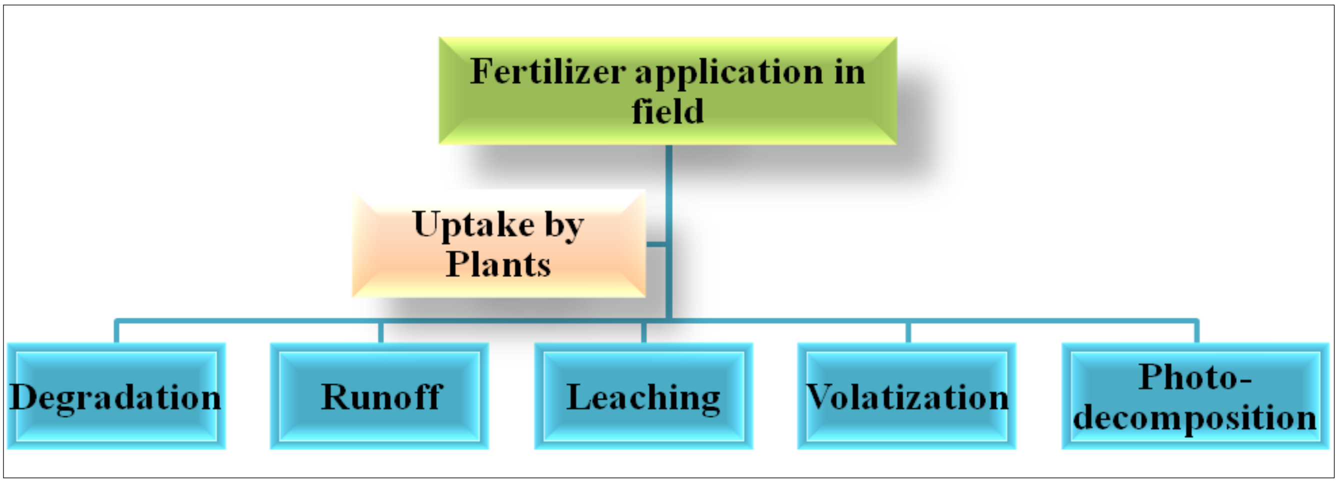

Fig. 1. Fate of fertilizer application in the field.

increase agricultural yields. They are the result of another invention that may have farming uses, although there are several flaws in their strategy. In any case, a few definitions similarly include various items, such as nano-biosensors and nano-scale movement systems (14). The disengaged implications of nano-fertilizers perplex the consistent community. The broader implications of nano-fertilizers continue to be unclear and remain the task of the medical network. Researchers are still trying to recognise their long-term results on soil ecosystems, nutrient cycling, plant body structure and environmental safety. This uncertainty leads to a deeper investigation into their conduct, endurance and ability to recognize dangers earlier than big-scale adoption. Nano-fertilizers are nanotechnology-based agricultural inputs designed to enhance nutrient delivery (15). They are distinct from compost, which is an organic amendment produced through biological decomposition. This flaw has led to a lack of consensus about the classification of nano-fertilizers, which might lead to poor decisions when evaluating their applications and potential advantages. Additionally, the substance utilized is taken into consideration when classifying nano-fertilizers.

For instance, carbon nanotubes are used to make certain nano-fertilizers, whereas metals or polymers are used to make others (16). Every type of nanofertilizer has unique qualities and the capacity to affect plant development. Plants can receive nano-fertilizers by foliar, soil and water application (Fig. 2). Three types of nano-fertilizers may be distinguished: nano-nutrient formulations of micronutrients, nano-nutrient formulations of macronutrients and nanomaterials loaded with nutrients. Among these groups, supplement nano-carriers are far more common than supplement nano-materials and they provide advantages in terms of health and environmental friendliness.

The ideal distribution of manures within nano-carriers considers the specific needs of the plants (Fig. 3). This determines and provides the principal procedures hired inside the layout and formulation of nano-fertilizers. Top-down techniques, which include mechanical milling and excessive-energy ball milling, reduce bulk materials into nanoparticles suitable for agricultural use, while bottom-up techniques, which include chemical precipitation, sol-gel strategies and green synthesis, build nanoparticles from atomic or molecular precursors with particular manipulation over size and composition (17). Encapsulation and coating techniques, using polymers, zeolites, clays, or chitosan, permit managed nutrient release and progressive retention in soil. Biostimulated and microbial synthesis strategies make use of plant extracts or microorganisms to provide nanoparticles in an eco-friendly manner,

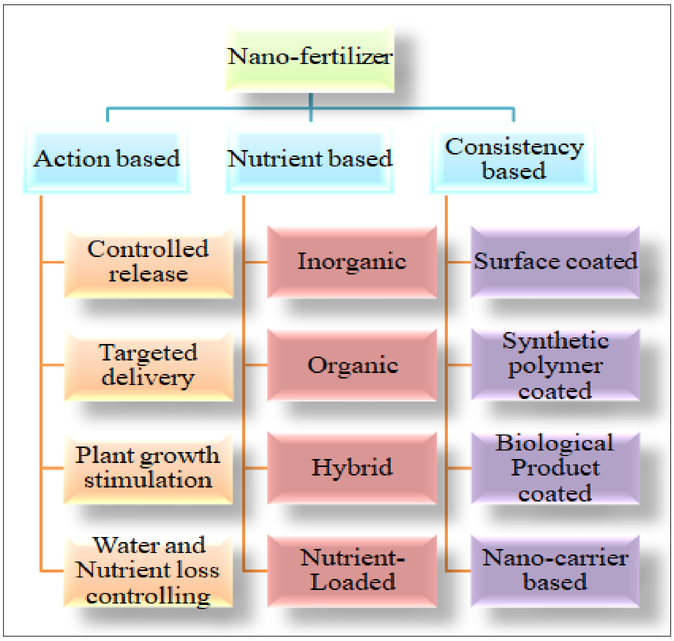

Fig. 2. General classification of nano-fertilizer.

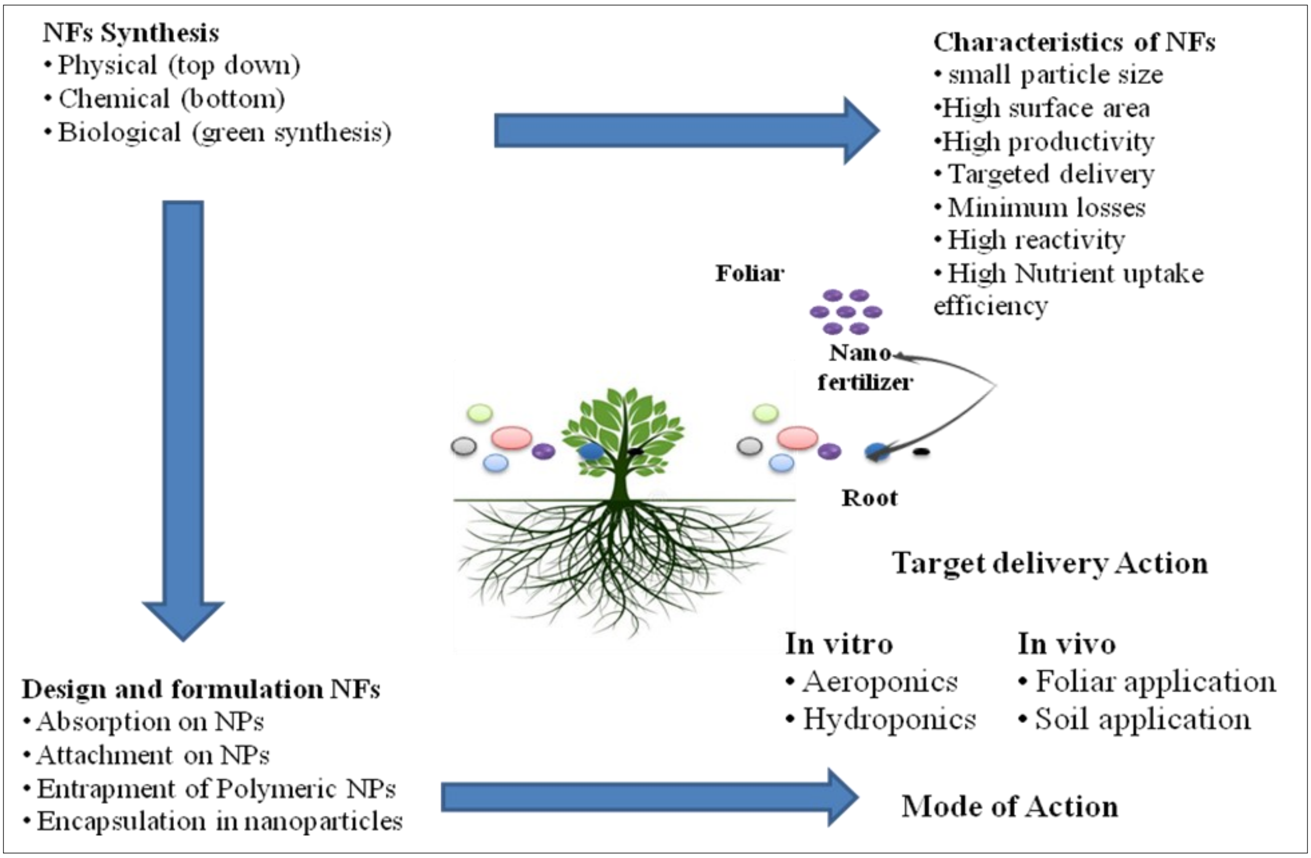

Fig. 3. Overview of design and formulation of nano-fertilizers based on the respective method.

improving biocompatibility and sustainability. Finally, formulation strategies combine nanoparticles into foliar sprays, seed coatings, or soil amendments to improve nutrient uptake, minimize losses and sell sustainable crop booms (18). Together, these techniques spotlight the flexibility of nanotechnology in agriculture, supplying advanced nutrient shipping, reduced environmental impact and improved crop productivity. Various nanomaterials have been used for the epitome and controlled arrival of manures, including mesoporous silica, carbon-based nanomaterials, polymeric nanoparticles and nano-clays. Applications for controlled-discharge nano-carriers may be found in manures, as well as in systems for the transportation of food, medicine and insecticides (19).

Action-based nano-fertilizers

Activity-based, controlled-release, targeted conveyance, plant development promotion and water and supplement impoverishment management are the five categories of nano-fertilizers. Innovative composts are crucial for practical agriculture since they provide several advantages, such as improved plant development, reduced nutrient loss, conserved nutrient release, designated nutrient conveyance and optimized supplement utilization (20).

Nutrient-based nano-fertilizers

Nutrient-based nano-fertilizers are fertilizers wherein the nutrient itself-consisting of nitrogen, phosphorus, potassium, or micronutrients-is formulated on the nanoscale or encapsulated inside nanocarriers. Their number one motive is to increase nutrient solubility, decrease losses through tactics like leaching or volatilization and improve the bioavailability of nutrients for plant life. Due to their nanoscale size, these fertilizers have a larger surface area and increased reactivity, which allows for controlled and sustained nutrient release. This ensures that plants acquire essential nutrients more efficiently over time, thereby enhancing nutrient use efficiency and supporting sustainable agricultural practices (21).

Consistency-based nano fertilizers

Consistency-based nano fertilizers combine surface-covered and nano-carrier-based technologies to provide a sustainable option for agriculture, with advantages such as enhanced supplement ingestion, reduced supplement discomfort and little environmental effect (22). Surface-covered nano fertilizers are defined as nanoparticles that are coated in biological materials and polymers. Natural item coatings like alginate can increase phosphorus accessibility and absorption, whereas manufactured polymers like polyacrylamide can increase the effectiveness of nitrogen consumption. Utilizing transporters such as mesoporous silica nanoparticles, nanocarrier-based nano fertilizers can influence the solubility, stability and accessibility of the supplement, hence increasing crop yields (23).

Techniques and resources for precision delivery of nanoparticles

Nano-fertilizers are frequently composed of tiny particles of metal oxides, such as zinc oxide or titanium dioxide, as well as polymers, like polystyrene or polyethylene. These materials all have unique qualities that make them appropriate for fertilizer delivery. Zinc oxide and titanium dioxide, for instance, are very porous and readily transport nutrients to growing cells. Conversely, polymers are more adaptable and may be designed to gradually disperse nutrients, resulting in a more controlled and accurate distribution (24). Plants can get nano-fertilizers directly by splashing, dousing and coating, or indirectly through soil application. Splashing is the most well-known application technique in farming since it is very simple to apply and should be possible in a short period of time. It is crucial to realize, nevertheless, that because of their tiny size, nano-fertilizers can be swiftly removed by water systems or precipitation. Applying them in a manner that ensures the preservation of the particles within the soil is therefore crucial. Coating and dousing are two other popular conveyance techniques (25). These have some control over the nutrient arrival over time and guarantee that the compost is dispersed uniformly throughout the soil. When applied to plants, the waxy skin of the fingernails should permit nano particles (NPs) to flow through, acting as a natural barrier that shields the leaves from water damage. In any case, NPs between 0.6 and 4.8 nm can enter the leaf via both hydrophilic and lipophilic routes, depending on the extremity or non-extremity of the solute. Additionally, it has been noted that NPs larger than 5 nm have little trouble entering the leaf. Transmission electron microscopy and confocal laser optical microscopy have been used in studies to investigate how plant species absorb NPs. The findings show that the NPs penetrate the leaf and go to the root through the vascular system (26). The phloem channels carry photosynthetic and other mixtures from the passages on to the roots, where they also carry NPs. NPs can also be absorbed through the pores in the underground roots of higher plants. Once inside the root, NPs pass through the cell wall and enter the intercellular space. NPs, on the other hand, are taken up via a transport channel that connects cells, where they enter the cells' cytoplasm. These NPs are delivered to neighboring cells by plasmodesmata (27). Nanoparticle delivery from leaves to roots occurs in general via the xylem. Nano-fertilizers, when mixed with controlled-release structures, improve nutrient shipping efficiency, reduce application rates and nutrient losses and mitigate soil and water contamination, addressing environmental, social, health and financial concerns. These structures also decrease irrigation and artificial input requirements, preserving strength and resources. Stabilizers integrated into nano-formulations improve balance, dispersion, focused delivery, photocatalytic interest and controlled-launch behavior, ensuring particular nutrient availability to crops. Another method is to use emulsions (nano-emulsions, micro-emulsions and nano-dispersions) to help make dynamic chemicals more soluble.

Modes of nano-fertilizer application

Foliar, seed nano priming and soil treatment are the three primary strategies for administering nano fertilizer. Foliar application, which includes distributing nanonutrients directly onto plant leaves, takes into account rapid supplement absorption via the leaf surface. The technique is especially effective in regions where soil fertility is low or when supplements are urgently needed. However, the foliar application is susceptible to environmental factors such as temperature, moisture and wind, which impact the absorption of nutrients (28). Covering or absorbing seeds with a solution containing nano fertilizers before planting is known as seed nano-priming. Faster germination, more grounded seedlings and improved nutrient uptake throughout the vegetation are all benefits of the technique. It is especially helpful in places with poor soil quality or where a fast plant foundation is crucial. In any event, the best technique to centralize nanofertilizers is not always the same in order to prevent phytotoxicity. Using broadcasting, banding, or confined conditions to directly incorporate nano-fertilizers into the soil is known as soil treatment (29). Through filtration or volatilization, the method reduces supplement misfortune and ensures a slow and regulated release of supplements. The best choices for soil remediation are regions with high supplement maintenance limitations and situations with consistent precipitation patterns. To prevent ecological contamination or unequal nutritional qualities, the application should be properly planned. Since the method of applying nano-fertilizer changes depending on the kind of soil and environment, it is crucial for the best possible plant development (30). The choice is based on environmental factors, soil quality and supplement accessibility, all of which affect supplement uptake and usage. By comprehending these factors and selecting the appropriate approach, agricultural operations may be made more sustainable, crop output can be increased and ecological impact can be decreased. The three application approaches are explained in detail below.

Foliar spray

Foliar shower is a high-level approach that directly applies fluid manures to plant leaves or foliage, allowing for rapid supplement absorption via the leaf surface. The technique employs nano-manure conveyance to the leaf surface for the targeted, ideal, quick and accurate contact with the plant. The foliar application of NPs is a promising way to deliver the necessary components, such as nano-composts, fungicides, herbicides and additives, to plants (31). This approach uses postponed discharge mechanisms to boost the sufficiency of these substances. Foliarly applied NPs can be assimilated via stomata, endocytosis, or direct ingestion, albeit the interaction is mostly dependent on the size of the molecule. The particle update may be restricted by the barrier-like effects of cell walls and leaf wax. Following ingestion, maximum NPs collect in vacuoles (32). However, NP absorption and transport are influenced by a number of parameters, including particle characteristics, NP actual properties and ambient circumstances. Less filtration and runoff, better supplement utilization and quicker responsiveness are some benefits of the foliar shower over conventional soil treatments (33). Applying nano-composts topically has been shown in several studies to increase agricultural productivity, encourage plant growth and improve nutrient absorption. The application of carbon-based NPs and Chief enhanced wheat production by 36.6 % and tough melon yield by 28 %. Foliar treatment of copper (Cu) NPs on tomato plants reduces the necessary copper concentration by 30 % while increasing natural product yield by 80 % when compared to traditional copper-based fungicides (34).

Seed nano-priming

In order to promote faster germination and advance plant development and improvement by guiding the metabolic and flagging processes, seed preparation is a pretreatment of plants that starts physiological changes inside seeds (35). The method incorporates absorbent seed nano-manures, which have been shown to achieve amazing results while halving the amount of compost that is applied. By penetrating seed pores, dispersing therein and activating plant compounds that promote growth, nano-biofertilizers function as energizers, improving germination and progress (36).

Soil treatment

To control nano-fertilizers for the soil, standard practices like broadcasting, side-dressing, or fertigation can be used. The NPs interact with the plant after they are in the soil by either sticking to the root surface or entering the root cells by endocytosis. When applied to soil, nano-fertilizers can interact with microorganisms, plants and soil particles, possibly changing their capabilities and behavior (37). The plants' development and production are enhanced by the NPs' controlled release of supplements, which guarantees a consistent supply of vital components (Table 1). Although this application approach is thought to be sound, it is subject to regulatory obstacles, higher expenses and questionable long-term consequences of nanoparticles (38).

Benefits of nanofertilizers compared to traditional chemical fertilizers

When compared to traditional manures, nano-fertilizers have a number of advantages, such as increased efficiency due to the instantaneous delivery of essential nutrients to plants and reduced environmental impact due to the reduced amount of compost that is needed. This invention may reduce the negative effects of manure on the environment while simultaneously increasing agricultural yields (39). High supplement fixation, delayed supplement arrival and enhanced plant uptake are some advantages of nano-fertilizers. Additionally, using nano-fertilizers can improve the physical and chemical characteristics of soils, reduce the need for manure and lessen the environmental impact of agriculture. Compared to their traditional counterparts, nano-fertilizers boast higher supplement concentrations, enabling lower application rates. As a result, manure costs can be reduced and the associated environmental impacts of production and transportation are mitigated (40). Over an extended period of time, slow release nano-fertilizers can provide plants with a steady supply of nutrients, enhancing plant growth and production. Such nano-fertilizers can also help reduce the need for repeated manure applications and the amount of nutrients that seep into the ecosystem. Improved plant uptake of supplements can lead to increased growth and yield as well as fewer climate-related supplement mishaps. By using nano-fertilizers, the overall natural

Table 1. Overview of nano-fertilizers application methods in agriculture

Methods	Descriptions	Advantages	Examples/studies	Challenges	Reference
Foliar spray	Direct application of liquid fertilizers, including nanofertilizers, to plant leaves for rapid absorption through stomata, endocytosis, or direct uptake. Relies on delayed release mechanisms for enhanced efficiency.	Rapid response, improved nutrient utilization, decreased leaching/run-off. Promotes plant growth and increases yield.	CeO and carbon-based NPs increase yield of wheat by 36.6 % and yield of bitter melon by 28 %. Copper NPs in tomatoes increased fruit yield by 80 % with 30 % less copper usage.	Leaf wax and cell walls may act as barriers; absorption depends on particle size and environmental conditions.	(48)
Seed nanopriming	Pre-sowing treatment involving soaking seeds in nanofertilizers to enhance germination and growth by activating plant hormones and regulating metabolic pathways.	Faster germination, reduced fertilizer usage, improved stress resistance and stronger seedlings.	Chitosan NPs (0.1–0.3 %) in beans improved seed germination, radicle length and stress tolerance under salt stress by enhancing proline and chlorophyll a levels.	High cost of nano-fertilizers; potential for long-term environmental effects; advanced processing required.	(49)

effect may be reduced and compost efficiency can be further enhanced. Compared to traditional fertilizers, nano-fertilizers provide a number of benefits. Their improved efficiency in absorbing nutrients is one of the main advantages (41). Better fertilizer efficiency and less waste are made possible by nano-fertilizers, which boost fertilizer consumption and enhance the ratio of plant nutrient absorption. Conventional fertilizers, on the other hand, are less successful, as plants do not absorb their bulk mixtures well. Through encapsulation, which is frequently mixed with polymer resins, waxes and sulfur to guarantee a precise release over time, nano-fertilizers also offer controlled release of nutrients (42). Conventional fertilizers, on the other hand, have a tendency to release nutrients in excess, which might be hazardous and upset the natural equilibrium. Another advantage of nano-fertilizers is that they improve the solubility and dispersion of previously insoluble mineral components in the soil, which increases their bioavailability for plants. However, traditional fertilizers are less available because of their larger particle size and weaker solubility. Additionally, nano-fertilizers lengthen the plants' rate of nutrient absorption by increasing the effective duration of nutrient release (43). Show the advantages and issues of nanofertilizer application in the field: when conventional fertilizers are distributed as insoluble salts, they often result in nutrient loss. Additionally, nano-fertilizers reduce leaching, runoff and drift-all major issues with conventional fertilizers that often lose a lot of plant nutrients via these processes. When compared to conventional fertilizers, nano-fertilizers offer a number of benefits, some of which are mentioned below (Table 2).

Limitations and potential risks related to the application of nano-fertilizers

Despite the promising outcomes, reports of different cutoff levels and negative consequences when using nano-composts have surfaced. The majority of the studies on nano-manure have only been done in a lab setting on a tiny scale. The need for a large usable leaf area and the danger of burning-or being too high to even consider reproducing if the shower focuses-are the disadvantages of foliar application of nanotechnology composts (44). Their effectiveness is affected by the climate; thus, they should be used at the right time. The following problems need to be looked at further: the nanoparticles' uneven size, the normalization of the nano details and the ease of using the nano manures on leaves. Observing how feeding affects the temperature and causes changes in the plant that supplies these particles inside the pastures is ineffective. It is yet unknown if all nano-manures undergo complete conversion to ionic structures inside the plant and are then integrated into proteins and other metabolites, or if some endure faultlessly and make their way to consumers through the natural order of things (45). To fully grasp the benefits of the nanomaterials, it is crucial to have more in-depth information about the materials' representation, do point-by-point evaluations with non-nano details and carry out field research (Fig. 4). The creation of nano-manures is one of the many applications of nanotechnology in agriculture, which is a fast-growing sector (46). These nano-manures have the potential to improve plant growth, decrease supplement accidents and boost supplement availability. In any case, not every possible concern related to the use of nano-composts has been carefully considered.

Human well-being dangers

The possible influence of nano-manures on human health is one of the main concerns surrounding them. Due to their small size, biological forms may surely retain NPs, which might lead to potential injury. Reviews have shown how ingesting nano-manures can damage an exploratory creatures' liver, kidneys and gastrointestinal tract (47). Additionally, NPs have the ability to pass through organic barriers like the blood-cerebrum border, which may result in neurological damage. To fully understand the long-term effects of nano-manure openness on human well-being, more research is anticipated (48).

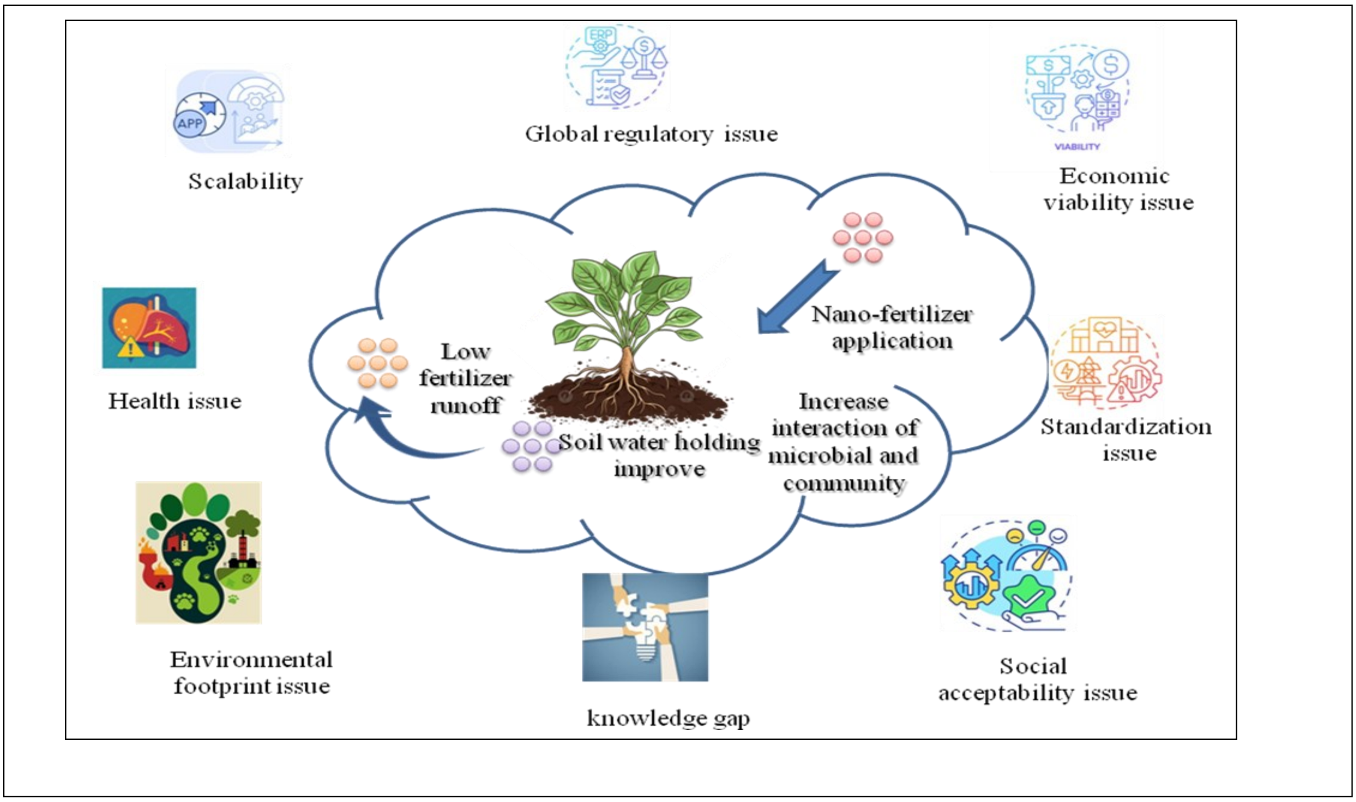

Fig. 4. Advantages and issues of nano-fertilizer application in the field.

Table 2. Properties and benefits of nano-fertilizers in agriculture

Property	Descriptions	Examples	Key benefits	Reference
Greater surface area	Nanofertilizers, with particles smaller than 100 nm, nutrient uptake enhancement due to increased surface area, enabling better plant nutrient penetration and supporting diverse metabolic functions of the plants, leading to an increased photosynthate production.	Nano-ZnO, Nano-$CuSO_4$	Increased nutrient uptake and utilization, enhanced photosynthetic production and improved efficiency in nutrient delivery to plants.	(52)
High solubility	Nano fertilizers have improved solubility because of their small particle size as well as large surface area, promoting dissolution inside the soil and increased availability of nutrients for plants and other organisms.	Nano-hydroxyapatite, Nano-zinc oxide	Enhanced nutrient availability in soil, improved bioavailability, better performance in a variety of solvents, leading to more efficient plant nutrition.	(52)
Encapsulation of fertilizers	Encapsulation techniques such as polymer-based methods, formation of an inorganic shell and layer-by-layer assembly increase nutrient absorption in crops, reduce nutrient loss and improve nutrient availability over time.	Zeolite-based nano-fertilizers, Polymeric nano-capsules	Increased nutrient retention in soil, controlled nutrient release, reduced nutrient loss due to leaching and enhanced plant growth over time.	(51)
Easy penetration and controlled release	Nano-fertilizers improve nutrient penetration into plant tissues because of their small particle size and higher surface area, enabling targeted delivery and reducing leaching and runoff. This leads to better yields of the crops and sustainability.	Nano-urea, Nano-ZnO	More efficient fertilizer use, reduced environmental impact from runoff, better targeting of nutrients to plant roots, leading to higher crop yields.	(52)
High nutrient absorption efficiency	Nano-fertilizers improve effectiveness of the fertilizer and the ratio of nutrient absorption in crops, minimizing fertilizer use and nutrient loss through leaching.	Nano-Zinc oxide, Nano-Fe_3O_4	Increased absorption efficiency, less fertilizer wastage, higher crop productivity and reduced environmental impact from leaching and runoff.	(49)
Effective duration of nutrient release	Nano-fertilizers release nutrients over an extended period, limiting the need for repeated applications by minimizing nutrient loss. Studies show that nutrient release can last from 45 to 60 days, depending on factors like nanoparticle size and coating.	Chitosan-coated nano-fertilisers, Polymer-coated nano-fertilizers	Extended nutrient release, fewer applications required, improved crop nutrition and reduced environmental contamination.	(52)
Improved microbial activity	Nano-fertilizers improve microbial activity in soil by facilitating better delivery of nutrients to the root zone and promoting the growth of beneficial microbes, which enhances soil fertility and plant growth.	Nano-encapsulated biofertilizers, Gold NPs	Enhancement of soil fertility, better plant growth, improved microbial health, better nutrient cycling and increased soil biodiversity.	(52)
Improved soil activity	Nano-fertilizers enhance soil activity by improving decomposition and nutrient cycling. They increase nitrogen mineralization rates and promote the activity of soil bacteria and fungi, important for maintaining the health of the soil.	Nano-silica, Nano-carbon NPs	Enhanced nutrient cycling, improved soil structure, greater soil microbial action and better decomposition of the organic material improve overall soil health.	(49)
Improved soil water-holding capacity	Nano-fertilizers enhance soil structure, aggregation and water-holding capacity, reducing soil erosion as well as water loss through runoff, leading to better crop yields and improved soil health.	Clay-based NPs, Carbon-based NPs	Improved soil aggregation, better water retention, reduced water runoff, enhanced soil erosion resistance and healthier soil structure for better crop yields.	(50)
Ecofriendly nature	Nano-fertilizers are safer for the environment than conventional fertilizers, reducing the risk of nutrient runoff and minimizing pollution due to their slow-release nature and higher nutrient efficiency.	Nano-hydroxyapatite, Nano-organic fertilizers	Reduced environmental impact, better nutrient management, lower fertilizer input and minimal pollution, promoting sustainable agriculture.	(49)
Low production cost	Nano fertilizers are cost-effective due to reduced fertilizer input, higher absorption rates and fewer applications needed, lowering production and labor costs.	Nano-urea, Nano-K_2O	Lower overall production and application costs, reduced labor and fertilizer input, improved resource use efficiency and higher agricultural productivity.	(50)
Fulfillment of precision farming goals	Nano fertilizers support precision farming by enabling more precise nutrient delivery for plants, reducing fertilizer use as well as soil runoff and enhancing crop nutrition management.	Nano-liquid fertilizers, Targeted delivery systems	Enhanced precision in nutrient delivery, reduced environmental impact, lower fertilizer use and improved crop yields through optimized input management.	(52)
Improves plant stress tolerance	Nano-fertilizers help plants in tolerating environmental stressors, like drought or extreme temperatures, by providing essential nutrients and protective compounds like antioxidants.	Nano-silicon, Nano-calcium	Enhanced plant resilience to abiotic stress, improved plant health under adverse conditions and better overall crop productivity in challenging environments.	(51)

Natural dangers

Air, water and soil contamination may result from NPs entering the climate. NPs have the potential to clump together in the soil, disrupting soil ecosystems and reducing soil fertility. Moreover, NPs that are drained from the soil into oceanic biological systems may negatively affect marine life, leading to bioaccumulation and biomagnification within the food chain. To prevent unfavorable outcomes, more research is necessary to determine the possible risks associated with the release of nanoparticles into the atmosphere (49).

Biological dangers

The anticipated impact of nano-composts on non-target organic entities is another major concern. Research has demonstrated that exposure to NPs can have antagonistic effects on a variety of organic organisms, such as fish, birds and insects. Nano-manures can hinder the growth, development and progress of organic organisms, thereby leading to population decreases. The impact of nano-composts on beneficial microorganisms, such as mycorrhizal symbiotic and nitrogen-fixing bacteria, is not well understood. To evaluate the potential environmental risks of using nano-compost, more research is necessary (50).

Current status and future directions

By reducing the natural effect of conventional fertilizers, the use of nanoparticles in manures ensures effective supplement delivery to the plants, increasing crop efficiency. A range of nanomaterials, including metal oxide nanoparticles, nano-zeolites and nano-chitosan, are being investigated by experts for their potential to enhance soil management and augment stomach muscle sorption. Significant progress has been made in the creation of controlled-discharge nano-fertilizers that continuously supply supplements, reducing the frequency of applications and potential supplement losses. The development and use of nano-fertilizers in agriculture depend on a focus on crucial areas of creative endeavor. Nano-fertilizers have a promising future in agriculture due to their numerous potential benefits. Nevertheless, future research on nanofertilizers should concentrate on developing economical and environmentally friendly amalgamation techniques for various nanomaterials, optimizing their physicochemical properties and lowering any hazards associated with their application. We genuinely want Web of Things (WoT) and Green technology innovation (GTI) advancement to produce dependable, affordable and biodegradable items in the future. All improvements significantly reduce environmental damage, impact and degradation and promote the expansion of regular asset usage. To provide nutrients where they are needed, efforts must be taken to arrange the specifics that enable the regulated and targeted administration of supplements using shrewd nano-fertilizers that can respond to certain natural cues, such as pH or temperature. By improving plant supplement usage efficiency and reducing supplement mishaps, this strategy can support sustainable agricultural methods. Including nano-sensors in nano-fertilizers should allow for continuous monitoring of soil supplement levels because they allow for precise application and less waste of supplements. With the help of this technology, ranchers may more effectively apply the proper amount of compost, increasing agricultural yields and reducing environmental pollution. Understanding the possible harm that nanofertilizers might do to the environment and human health, as well as creating clear legislative frameworks and industry standards to guarantee their safe and effective use, should be the main goals of future study. Investigating the possible harm that nano-fertilizers may cause to crops, humans and soil organic matter is essential to guaranteeing their long-term safety. Ultimately, training and a campaign targeted at ranchers and other partners are needed to promote the adoption and implementation of nano-fertilizer in agriculture. It may be accomplished by raising awareness of the benefits of nanofertilizers as well as their safe, healthy and efficient use. By adopting precision agriculture, which includes drones with cameras that can take multispectral pictures to pinpoint supplement focus in the field, or by overusing the yields, ranchers may prevent squandering precious resources.

Research should be conducted to lower hazards and boost advantages from prospective possibilities and cooperative energies that the use of nano-fertilizers may provide for the long-term survival of agricultural terrains. However, developing and using these particles to boost food production with improved nutrient efficiency requires weighing the potential biological effects and yield benefits against the costs and natural resources of production (51). Given this, a daily life cycle study of nanoparticles might offer a comprehensive assessment of their use by considering their yield efficiency, ecological ramifications and impact on natural pecking orders. Another unsolved difficulty is assessing the benefits and drawbacks of nano-fertilizers in suitable field settings to satisfy partners' interests before they are extensively employed (52).

Conclusion

Nano-fertilizers display strong potential to improve nutrient efficiency and decrease environmental impact, indicating that the research hypothesis is normally supported. Their industrial promise lies in scalability, price-effectiveness and suitability for sustainable farming, specifically in growing regions. However, demanding situations, which include improving nanomaterial dispersion, optimizing release behavior and growing bendy huge-scale manufacturing structures, must be resolved for industrial adoption. At the same time, long-term environmental and health dangers require strict guidelines and protection protocols. Training farmers on application techniques and dangers will further help responsible use. Overall, nano-fertilizers seem both environmentally and economically promising with persevered innovation.

Acknowledgements

Authors are thankful to the ICAR-Indian Agricultural Research Institute, New Delhi; ICAR-National Academy of Agricultural Research Management, Hyderabad, Telangana; Agriculture College, PJTAU, Warangal; Acharya N. G. Ranga Agricultural University, Naira, Andhra Pradesh and all the institutes from where the people collaborated and resulted into this successful publication.

Authors' contributions

SS contributed to conceptualization, writing of the original draft, reviewing and editing of the manuscript and supervision of the study. SKS contributed to literature review and data curation. BSSSN contributed to data curation and investigation. KJ contributed to methodology development and validation. AB contributed to visualization and formal analysis. BR contributed to validation and provision of resources. CR contributed to resources and investigation. AS[1] contributed to writing review and editing. BSK contributed to investigation and data curation. SP contributed to writing of the original draft. JN provided technical support and software assistance. AS[2] contributed to manuscript review. TS contributed to formal analysis and data curation. PG contributed to supervision and project administration. JSB contributed to interpretation of results and validation. KV contributed to software handling and visualization. DAR contributed to proofreading and writing review and editing. AS[3] contributed to final approval and validation of the manuscript. All authors read and approved the final version of the manuscript. All authors read and approved the final manuscript [AS[1]- Aishwarya Sharma; AS[2]- A Sathish; AS[3]- Adarsh Sharma].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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