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Nanofertilizers for sustainable crop nutrition and production: A review

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Abstract
Agriculture worldwide faces major challenges from growing populations, declining fertilizer performance, and environmental damage from overusing conventional fertilizers. Traditional fertilizers work poorly—crops absorb only 10-20% of applied phosphorus and 30-60% of nitrogen, while the rest is lost through leaching and runoff, damaging soils and polluting water. Nanotechnology offers a better solution through nanofertilizers that release nutrients slowly, improve availability, and increase plant uptake. In this review, we discuss different methods to make nanofertilizers (top-down, bottom-up, and biological), along with various types such as nanoscale inputs, additives, and coating materials. Carrier systems like nano-zeolites, nano-chitosan, and nano-biochar hold and release nutrients much better than conventional fertilizers, lasting 40-50 days instead of just 4-10 days. Different application methods like seed coating, soil mixing, drip irrigation, and foliar spraying are greatly improving crop growth, yield, quality, and stress tolerance. Nanofertilizers boost nutrient efficiency significantly, with biosynthesized forms reaching 80-85% nitrogen efficiency compared to only 30-35% for conventional sources, while reducing pollution. However, concerns about nanoparticle toxicity at high levels, production costs, and long-term environmental effects need more research for safe agricultural use.

Keywords: Nanofertilizer, green synthesis, mode of fertilizer application, slow-release nanocomposite fertilizer

1. Introduction

World food production and distribution are facing huge stress due to increasing population, climate change, environmental contamination, and higher demands of water and energy. According to Food and Agriculture Organization (FAO, 2017) [33], world's population is projected to reach 10 billion by 2050 boosting food requirements by 50% especially in the developing countries (Usman *et al*., 2020) [139]. Since the Green Revolution transformed agriculture, synthetic fertilizers have become vital tools for boosting crop yields and improving plant nutrition, particularly with the development of high yielding varieties that respond well to fertilizer applications. Today, farms around the world depend heavily on chemical fertilizers to produce enough food for our growing population.

India's experience illustrates this dramatic shift. Between 1970 and 2020, the country saw fertilizer use skyrocket while international raw material prices climbed steeply. The partial factor productivity measured as kilograms of food grain produced per kilogram of fertilizer nutrient used, declined sharply from 28 kg kg^{-1} in 1970-71 to just 10 kg kg^{-1} in 2019-20 (FAI, 2020) [32]. This declining efficiency, paired with excessive and imbalanced fertilizer use, has created serious environmental problems: degraded soil quality, polluted waterways, and rising greenhouse gas emissions.

Traditional fertilizers come with significant limitations. Their chemically reactive forms make them difficult for plants to absorb effectively, and they lack proper controlled-release properties. As a result, huge amounts of nutrients are lost through leaching, evaporation, and runoff. Studies show that crops absorb only 10-20% of applied phosphorus, 30-60% of nitrogen, and 30-50% of potassium, meaning 40-90% goes to waste, creating both economic losses and environmental harm (Solanki *et al*. 2015) [124].

Consequently, the heavy application of synthetic fertilizers is often required to enhance crop yields, leading to increased production costs and reduced profit margins for farmers. Over time, this can cause severe environmental issues, including air and groundwater contamination, soil degradation, and water eutrophication. Growing concerns about pollution, chemical residues, and ecosystem damage have intensified pressure to reduce synthetic fertilizer use. As a result, agriculture now requires more efficient and sustainable nutrient-management strategies, making practical innovations like nanotechnology essential for advancing precision farming and supporting long-term crop productivity.

Nanotechnology plays a vital role in precision agriculture focusing on the potential of nano-based fertilizers, pesticides, sensors, and nanomaterials to increase agricultural efficiency, reduce environmental impact, and ensure food security for the growing global population (Arora *et al*., 2022; Hatti *et al*., 2020) [14, 45]. The progress in agriculture owes much to the efficient use of nanomaterials, which require smaller amounts compared to traditional ones.

Nanotechnology is defined as the branch of science which deals with the characterization, fabrication and manipulation of materials at nanoscale (Handford *et al*., 2014) [44]. It involves the understanding and control of materials within the 1-100 nm range in at least one dimension (EPA, 2007) [31]. Nanoparticles (NPs) exhibit significantly different physical, chemical, electronic properties exhibit differently from bulk materials due to their small size and high surface area. They also have high charge density and reactivity, facilitating their interaction with other compounds (Adhikari *et al*., 2010) [4]. NPs have unique properties including shape, size, large surface area, crystallinity, surface functionalization, porosity, zeta potential and hydrophobicity, or hydrophilicity, that allow the targeted controlled release kinetics of NPs to be used as smart delivery systems (Solanki *et al*., 2015) [124].

2. Nanofertilizer: An overview

Nanofertilizers are fertilizer formulated using nanotechnology that can systematically release nutrients to targeted plant sites, control deficiencies while preserving soil structure, and utilize nanosized materials as carriers and vectors for controlled release, thus collectively termed as smart fertilizers. Their unique features enhance plant performance by improving absorption, boosting photosynthesis, increasing yield, and expanding leaf surface area (Naderi and Danesh-Shahraki, 2013).

Most nanofertilizers feature slow or continuous nutrient release, often achieved through nanoencapsulation within nanocarriers or nanocoating. This mechanism helps prevent eutrophication and reduces water pollution. Their release can also be designed to respond to environmental stimuli such as pH, moisture, and temperature changes (Nongbet *et al*., 2022). They are nanomaterials that serve as plant nutrients or carriers for nutrients. They have high solubility in different solvents and their particle size, facilitates more penetration of nanoparticles into the plant from applied surface such as soil or leaves (Qureshi *et al*., 2018) [98].

Nano fertilizer enhance soil fertility, nutrient bioavailability, and product quality. Their large surface areas and slow steady nutrient release make them ideal for modern agriculture (Prasad *et al*., 2017) [93].

IFFCO accelerated India's shift toward nanofertilizers by introducing nano nitrogen, nano zinc, and nano copper in 2019, followed by the launch of the world's first nano urea in 2020 to reduce dependence on conventional fertilizers and improve nutrient efficiency. With the 2021 Fertilizer Control Order amendment establishing regulatory standards and the rollout of nano DAP in 2023, IFFCO strengthened its role in advancing sustainable, high-efficiency fertilizer technologies aligned with national food security goals.

3. Comparison of nanofertilizers and conventional fertilizers

Traditional fertilizers need to be applied in large amounts, as they have low uptake efficiencies. The two main challenges for phosphorus and nitrogen based fertilizers are low nutrient uptake efficiency and rapid change into chemical forms that cannot be utilised by plants. This has had a negative impact on the soil and the environment, as the emission of dangerous greenhouse gases and eutrophication have increased (Raliya *et al*., 2017) [100].

Nanofertilizers gradually release nutrients, which may aid in improving nutrient use efficiency without any related adverse effects. These nanofertilizers are constructed in order to deliver nutrients slowly over an extended time period and to reduce nutrient loss considerably, thereby ensuring environmental safety (Ghormade *et al*., 2011) [39]. Growers can enhance crop development by using slow-release nutrients that provide steady nourishment over 40-50 days, compared to the 4-10 days of conventional fertilizers (Chen and Wei, 2018) [20, 141]. A comparison between nanofertilizers and conventional fertilizers is presented in Table 1, which illustrates how both types differ in terms of efficiency, release behavior, and agronomic impact.

Table 1: Comparison of nanofertilizers to conventional fertilizers (Cui *et al*., 2010) [23]

Properties	Nanofertilizers	Conventional fertilizers
Solubility and dispersion of mineral nutrients	High	Low
Nutrient uptake efficiency	Increased uptake ratio; saves fertilizer resources	Low
Controlled release modes	Release rate and pattern are precisely controlled	Excess release leading to toxicity and soil nutrient imbalance
Effective duration of nutrient release	Extended effective duration	Immediately taken up
Loss rate	Reduced loss of fertilizer nutrients	High loss due to leaching, drifting, run off
Soil adsorption and fixation	Reduced	High
Bioavailability	High	Low

While comparing nanofertilizers with chemical fertilizers in terms of requirement and cost, nanofertilizers are economically cheaper and are required in lesser amount (Manjunatha *et al*., 2016) [73].

Nanoclay formulations such as zeolite and montmorillonite (30-40 nm) release nutrients for more than 1000 hours, far exceeding conventional fertilizers (Subramanian and Rahale, 2009) [130].

Overall, nanofertilizers increase nutrient-use efficiency, lower toxicity risks, and reduce the need for repeated applications (Naderi and Danesh-Shahraki, 2013).

Namdeo *et al*. (2023) [83] evaluated the impact of nano urea on the yield attributes, overall yield, and active ingredients in Ashwagandha (*Withania somnifera* L. Dunal). The study included various treatments: a control, split nitrogen applications

(40, 60, 80 kg ha^{-1}), and foliar nano urea sprays (0.2, 0.4, 0.6, 0.8, 1.0%) applied at 45 and 90 days after sowing (DAS). The foliar spray of nano urea 0.6% at 45 and 90 DAS achieved the best results, notably the highest economic yield (1708 kg ha^{-1}). This treatment outperformed conventional urea in leaf yield, root yield, biological yield, root harvest index, and protein content.

In *Brassica oleracea* var. sabauda, field trials using urea-hydroxyapatite and potassium sulfate nanoparticles at both full and half NPK doses showed that nanofertilizers at 50% of the recommended rate produced cabbage growth, yield, and nutrient composition comparable to conventional fertilization. Soil pH and available P increased over the crop cycle, while total N, C, CEC, and texture remained unaffected by fertilizer type or dose. Overall, the study demonstrates that nanofertilizers can maintain crop performance while reducing nutrient inputs, highlighting their potential as a more sustainable fertilization strategy (González-Feijoo *et al*., 2024) [40]

A field experiment evaluated the economic and environmental performance of conventional fertilizers with and without nano-urea in maize-wheat and pearl millet-mustard systems under semi-arid Indian conditions. Supplying 75% of the recommended nitrogen through conventional fertilizer combined with nano-urea foliar spray (N75PK + nano-urea) reduced energy use by ~8-11% and improved energy efficiency by ~6-9% compared with the standard 100% N through prilled urea. This treatment also produced ~14% higher economic yields than N50PK + nano-urea and maintained soil N and dehydrogenase activity at levels comparable to full conventional fertilization (N100PK). Notably, two nano-urea sprays enabled a 25% reduction in nitrogen input without yield loss, while lowering GHG emissions (164.2-416.5 kg CO_2-eq ha^{-1}) across crops. Overall, applying nano-urea with 75% prilled urea represents an energy-efficient, environmentally resilient, and economically viable nutrient management strategy for sustainable production (Upadhyay *et al*., 2023) [138].

4. Classes of nano fertilizers

The three categories of nanotechnologies for fertilizer inputs and plant protection are described below (Mastronardi *et al*., 2015) [75]:

4.1. Nanoscale fertilizer inputs

This category describes examples of a nanosized reformulation of a fertilizer input. The fertilizer or supplement is reduced in size, using mechanical or chemical methods, down to the nanoscale. The input is typically in the form of nanoparticles but may also be in other forms for example, ZnO NPs. Sary and Abd El-Aziz (2025) [113] investigated nano-fertilizer effects on maize productivity with treatments including Nano-Zn, Nano-Mn, and Nano-Mo (20 and 40 mg L^{-1}) compared to chelate and conventional forms, with nano-micronutrients. The 40 mg L^{-1} concentration of nano-fertilizers proved most effective, yielding highest grain weight per plant (239.4 g with Nano-Mo), 100-grain weight (40.7 g with Nano-Zn), and yield (15.1 ton/ha with Nano-Mn). Nano-Zn at 40 mg L^{-1} maximized leaf nutrient contents (P: 0.98%, K: 1.0%, Fe: 268 mg kg^{-1}, Zn: 79 mg kg^{-1}, Cu: 24.3 mg kg^{-1}), with nano-fertilizers demonstrating superior performance over traditional fertilizers in all parameters.

4.2. Nanoscale additives

This category includes examples where the nanomaterials are added to bulk (>100 nm scale) product. These nanomaterials may be a supplement material added for an ancillary reason, such as water retention or pathogen control in plants or soils for example, carbon tube-urea. Sharma *et al*. (2020) demonstrated that applying chitosan-based nanofertilizers doped with copper and salicylic acid to maize improved several physiological responses. Using chitosan ion-gelation to encapsulate the nutrients, the formulation enhanced antioxidant enzyme activity, lowered malondialdehyde levels, and increased leaf chlorophyll content, indicating a clear positive effect on plant stress status and overall performance.

4.3. Nanoscale coatings or host materials for fertilizers

This category describes nano thin films or nano porous materials used for the controlled release of the nutrient input. These include, zeolites, chitosan, clays, and thin polymer coatings. Nano-zeolite (90-110 nm) loaded with 14% Zn exhibited sustained nutrient release for 1,176 hours compared to 216 hours for conventional $ZnSO_4$, demonstrating its efficacy as a slow-release fertilizer for enhanced nutrient use efficiency in crops (Yuvaraj, M. and Subramanian, K.S., 2018) [144]

5. Synthesis of nano fertilizers

Nanomaterials can be developed from synthetic substances or green synthesized from plant materials through chemical, mechanical, or biological methods. There are three main synthesis approaches: (i) top-down and (ii) bottom-up and (iii) biological (Fig. 1&2).

5.1. Bottom-up method

The bottom-up, constructive or chemical route produces nanoparticles by assembling atoms or molecular units that serve as nanoscale building blocks, which subsequently organize into larger nanostructures. This approach encompasses techniques such as chemical vapor deposition, sol-gel processing, hydrothermal and solvothermal synthesis, templating strategies, reverse micelles, spinning, and various pyrolysis processes (Chan and Kwok, 2011) [19,]. These methods generally offer superior control over particle size, morphology, and purity compared to top-down strategies, owing to their atom-by-atom or molecule-by-molecule construction. However, they often depend on substantial quantities of chemical reagents and may require high temperatures or pressures, resulting in environmental and safety concerns that limit their sustainability. This method allows greater control of the size of the nanostructures and the reduction of impurities.

Kottegoda *et al*. (2017) developed environmentally friendly urea-hydroxyapatite nanofertilizers using a bottom-up synthesis in which phosphoric acid was added dropwise to a calcium hydroxide-urea suspension, producing nanostructures capable of controlled nutrient delivery. The resulting nanohybrid released nitrogen gradually for up to one week in aqueous media, whereas pure urea, due to its high solubility, would dissolve rapidly and provide no sustained-release behavior.

5.2. Top-down method

Top down or physical approaches reduce bulk materials to the nanoscale by mechanically disrupting the intermolecular forces mainly weak van der Waals interactions that stabilize their stacked structures. This breakdown yields thin crystalline fragments but requires extremely high energy inputs, making these methods economically unattractive. Common techniques include mechanical milling, laser ablation, nanolithography, sputtering, etching, electro-expulsion, and thermal decomposition (Ealia and Saravanakumar, 2017; Saravanan *et al*., 2021) [, 112]. Despite their conceptual simplicity, these processes often provide poor control over particle size and uniformity, and they may inadvertently modify the surface chemistry or other physicochemical properties of the material, which limits their suitability for precision nanomaterial production.

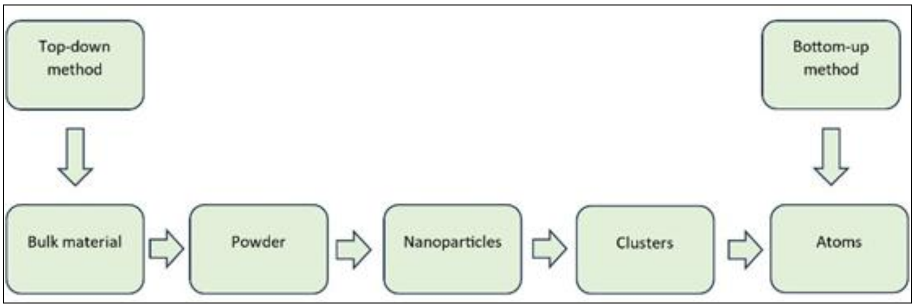

Fig 1: Synthesis of nanofertilizer

5.3. Biological method

Biological method or green synthesis is an environment friendly method, using bio-organisms like plant extract, fungi and bacteria as reducing and stabilizing agents without any harmful chemicals (Lee *et al*., 2020) [64]. The production of plant and microorganism derived NPs has emerged as an efficient biological source of nanofertilizers (Panpatte *et al*., 2016) [90]. The advantage of obtaining nanofertilizers via biosynthesis isthe low cytotoxicity of the final product (Cai *et al*., 2020).

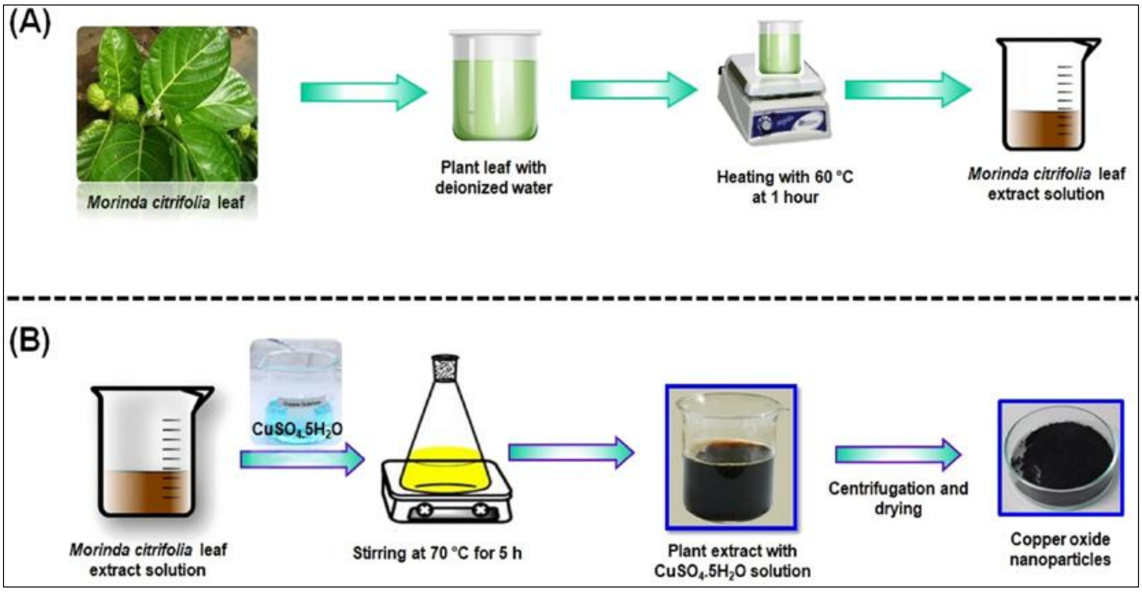

Fig 2: Green synthesis of copper oxide nanoparticles (Source: Priya *et al*., 2023) [94]

Table 2 showing fungal species with high efficiency in converting phosphorus salts (such as tri-calcium phosphate) into nano phosphorus particles through microbial biosynthesis, including the specific fungal strains and their corresponding phosphate sources, as documented by Tarafdar (2020) [132].The table 3 presents a comparative analysis of nutrient use efficiency (NUE) between conventional chemical fertilizers and biosynthesized nano-form fertilizers, evaluating their effectiveness in nutrient uptake and utilization by plants.

Table 2: List of some efficient fungi for nano phosphorous from phosphorous salts

Name of the Organism	Size of Nano-P (nm)
Aspergillus terreus CZR-1	11-74
Aspergillus flavus TFR-1	17-64
Aspergillus tubingensis TFR-3	5-49
Aspergillus fumigatus TFR-8	37-81
Aspergillus oryzae TFR-9	23-88
Emericella nidulans TFR-14	55-92
Rhizoctonia bataticola TFR-6	12-36

(Source: Tarafdar, 2020) [132]

Table 3: Comparison of use efficiency of a nutrients (NUE) added through chemical fertilizer and nano form of biosythesized fertilizer

Nutrient	NUE (%) added through	
	Chemical fertilizer	Nano fertilizer
N	30-35	80-85
P	15-20	58-65
K	35-40	82-88
S	17-22	75-78
Cu	2-5	77-81
Fe	4-5	80-82
Zn	3-4	78-80

(Source: Tarafdar, 2020) [132]

The nano fertilizers using biosynthesis, for the first time in the world was developed by Dr. Jagdish Chandra Tarafdar of the Central Arid Zone Research Institute under the ICAR. The fertilizer was prepared by developing a methodology to use microbial enzymes for breakdown of the respective salts into nano form. Since it is complete bio-source, nano fertilizers produced by biosynthesis is eco-friendly and improves soil aggregation, moisture retention and carbon build-up. There is no health hazard and is suitable for all crop varieties including food grains, vegetables and horticulture crops (Yaseen *et al*., 2020) [143].

Solanki *et al*. (2015) [125] described different methods to load nutrients into nanoparticle such as:

1. Absorption on nanoparticles
2. Attachment on nanoparticles mediated by ligands
3. Encapsulation in nanoparticulate polymeric shell
4. Entrapment of polymeric nanoparticles

6. Mode of fertilizer application

The mode of fertilizer application influences the efficiency of nanofertilizers and their impact on plant system. The following methods of application can be practiced in nanofertilizers (Dagade *et al*., 2020) [25].

6.1. Seed coating

The distance between the fertilizer and the seed has an impact on the plant's capacity to utilize nutrients. The combination of both materials into a unit of fertilizer coated seed may improve farming efficiency. Hence, closer the fertilizer to the seed, the smaller amount will be needed to develop a fully grown plant. Sharma *et al*. (2022) [119] proven that soaking seeds in nanofertilizers can significantly reduce fertilizer use without compromising quality. Thus, the effect of seeds coated with fertilizers will be more.

6.2. Soil application

Due to the nanostructured formulation of fertilizers, the release of nutrients into the soil happens gradually and in a controlled way which is beneficial to increase soil microbial population and enzyme activity.

Root uptake can substantially limit nutrient acquisition from soil applications because pore size restricts the movement of many elements. In a long-term evaluation on orange (*Citrus sinensis* (L.) *Osbeck*), Sartori *et al*. (2008) compared root and foliar absorption of zinc and found that, over five years, root uptake was the more effective pathway for supporting plant development.

6.3. Drip application

Drip irrigation is great at delivering water and nutrients right to plant roots, boosting nutrient use efficiency to 80-90% and improving both yield and quality. When paired with slow-release nanofertilizers, it helps to manage nutrients more effectively, making it an ideal solution for growing crops in arid and semi-arid areas.

Al-Juthery *et al*. (2019) [9] conducted an autumn field experiment to evaluate the effect of nano-NPK fertigation on the growth and yield of potato (cv. Arizona) under drip irrigation. Nine treatments including single, dual, and triple nano-NPK applications, conventional NPK (20:20:20), and a control were tested. The nano fertilizers were applied in four fertigations at increasing proportions. Among all treatments, the combined nano-NPK (N+P+K) produced the highest plant height, chlorophyll content, vegetative biomass, tuber yield (soft, dry, and total), and improved starch and protein content, significantly outperforming single and dual nano applications.

6.4. Foliar application

Nanoparticles can penetrate the stomatal pores with the size less than 50 nm, hence significantly augment nutrient absorption and aid in production as compared with traditional fertilizers. Raliya *et al*. (2017) [100] reported that foliar spray significantly outperformed soil application in terms of nutrient uptake, according to comparison research. Punnoose (2019) [97] reported that foliar spray of nano NPK 0.3 per cent at fortnightly intervals has significantly increased the fruit quality of okra compared to polyfeed spray at 0.5 per cent in rain shelter conditions.

Foliar uptake is a major pathway with high efficiency and reduced environmental contamination. Its limitations relate mainly to nutrient mobility and penetration through the leaf cuticle. Rios, Garcia-Ibañez and Carvajal (2019) tested Zn nanobiocarriers as foliar nanofertilizers in hydroponically grown broccoli and pak-choi (*Brassica rapa* subsp. *chinensis*) deprived of zinc. They evaluated formulations combined with a surfactant (PMP) and with plant-derived vesicles to enhance nutrient bioavailability. While zinc applied alone produced only a slight increase in leaf Zn concentration, the surfactant-assisted treatment tripled Zn accumulation, and the vesicle-plus-surfactant formulation yielded the highest uptake nearly fourfold compared to plants receiving zinc without additives.

Abdel-Aziz *et al*. (2019) [2] evaluated chitosan nanoparticles and modified carbon nanotubes used alone or NPK-loaded in French bean cultivation through seed priming and foliar application. Their results showed that foliar delivery outperformed seed priming, and chitosan nanoparticle sprays shortened the harvest period to about 80 days without compromising yield compared with the 110-day control. In contrast, foliar application of carbon nanotubes produced no notable improvements.

Azam *et al*. (2022) [15] evaluated nano-fertilizer application via soil (40-160 mg kg^{-1}) and foliar (10-40 ppm). Soil application enhanced plant growth, photosynthetic pigments, and antioxidant activity by 61.1%, 51.8%, and 49.25%, respectively compared to control, while foliar application increased these parameters by 59.28%, 48.19%, and 52.91%. ZnO nano-fertilizer effectively improved maize growth and yield, demonstrating potential for enhancing crop performance in Zn-deficient soils.

7. Transport models for nutrient uptake in plants

Nanoparticles enter plants through both roots and aerial tissues—via cuticles, stomata, trichomes, hydathodes, stigmas, wounds, and root junctions (Wang *et al*., 2016) [140]. After crossing the root epidermal wall and membrane, their movement toward the vascular tissues is largely size-dependent, with only particles small enough to pass through membrane pores able to penetrate efficiently (Liu *et al*., 2010; Gao *et al*., 2011) [66, 36]. Before reaching the stele, they move apoplastically, while internal uptake relies on active, signaling-mediated membrane transport, including endocytosis, ion channels, carrier proteins, and aquaporins (Nair *et al*., 2010) [82]. Larger particles typically enter through stomata or hydathodes and move mainly through the phloem, with ~40-50 nm representing the upper size limit for effective cellular entry and accumulation (Eichert *et al*., 2008; Tripathi *et al*., 2017; Sabo-Attwood *et al*., 2012) [, 106]. In seeds, uptake occurs through parenchymatous spaces moderated by aquaporins (Lee *et al*., 2010) [64].

Nanoparticle traits such as surface structure, charge characteristics, and aggregation tendencies strongly influence how they interact with plant cells. Because plant cell walls carry a net negative charge, nanoparticles with positive surface charges tend to bind more readily (Brindhav *et al*., 2025).

8. Slow-release nanocomposite fertilizers

Slow-release nanocomposite fertilizers are nanofertilizers offer economic benefits by providing a slow, sustained release of nutrients, minimizing losses from leaching and emissions, and ensuring consistent nutrient availability throughout the crop life cycle, making it both economically viable and socially sustainable (Anderson, 2010) [13]. Active ingredients can be incorporated into nanoparticulate systems either during particle synthesis, where the compound becomes embedded within the particle matrix, or after particle formation, where it is adsorbed onto the particle surface through incubation. Nano-based encapsulated and slow-release fertilizers improve nutrient uptake, enhance soil fertility, and reduce the toxic effects associated with fertilizer over-application. These smart delivery systems ensure nutrients are released slowly, targeting specific areas and adjusting to the crop's needs (Cui *et al*., 2010) [23]. The important crop based nanofertilizer or nano formulation were produced which effectively increase growth and yield of the crops without create any harmful effect in environment ecosystem (DeRosa *et al*., 2010). They use carriers such as nanoclays, chitosan, polymers, or metal-oxide matrices to trap the nutrients and release them slowly through diffusion, degradation, or environmental triggers (moisture, pH, enzymes).

The zeolite based nano porous fertilizer utilization and interest will increasing within young researchers in nano technology field (Ghafariyan *et al*., 2013; He *et al*., 2010) [47]. Jaberzadeh *et al*. (2013) [38, 54] reported that using silica nano mesoporous particle to encapsulate urea and produce nano nitrogen slow release fertilizer and also found that apatite as a source of nano phosphatic fertilizer.

A chitosan- montmorillonite (MMT) nanoclay hydrogel was developed by Dou *et al*. (2023) [29] as a low-cost, biodegradable controlled-release fertilizer matrix, significantly improving nutrient release uniformity, soil water retention, and biodegradability while preventing the rapid nutrient losses typical of conventional fertilizers. Overall, the composite released only 55.3% of its load over 15 days compared to 89.2% loss during the first irrigation with traditional fertilizers, highlighting its value for sustainable agriculture.

8.1. Nano zeolite

Nano zeolites' honeycomb structure allows for the exchange and absorption of liquids and gases, making them versatile for many residential and commercial uses (Smedt *et al*., 2015) [123]. Liu and Lal (2014) [66] stated that zeolite mesoporous particles are potentially useful for synthesizing nanofertilizers due to their high surface area (900 $m^2 g^{-1}$), which makes them exceptionally effective for ion exchange. Dhoke *et al*. (2013) [28] stated that nano-sized zeolite minerals possess a high surface area, significant nutrient absorption capacity, enhanced water retention, and a large number of internal micropores due to their favorable physical and chemical properties. Zeolite acts as a carrier of nitrogen, phosphorous, potassium and micronutrient fertilizers enhance the productiveness of crops (Mahmoodzadeh *et al*., 2013) [68].

Malhi *et al*. (2002) [69] stated that nanofertilizers formulated with zeolite can successfully deliver nutrients for up to 50 days, whereas traditional fertilizers like urea typically last only 10 to 12 days. Manikandan and Subramanian, (2014) [71] stated that nano clay like zeolite and montmorillonite carrying nitrogen are ability to deliver prolonged period of time (>1000 hr) than conventional fertilizers (<500 hr).

Nano-zeolites effectively regulate nitrogen release, and nano-zeolite encapsulated urea enhances nitrogen adsorption within the zeolite's mesoporous structure. Zeourea and nanozeourea, with nitrogen contents of 18.5% and 28% respectively, release nitrogen over 34-48 days, while urea alone releases nitrogen in just 4 days. Studies show that mixing urea 2 with zeolite and sago wastewater significantly improves the availability of ammonium and nitrate ions compared to urea alone (Markovich *et al*., 1995) [74].

A study conducted by Manikandan and Subramanian (2016) [72] evaluated the zeolite-based nitrogen nano-fertilizers on maize growth, yield and quality on alfisols at Tamil Nadu Agricultural University. There were five treatments that include Urea, Zeolite-Urea mix, Nano Zeolite-Urea mix, intercalated Zeourea, and intercalated Nanozeourea. The growth, yield & quality were consistently higher for nanozeourea treatment than conventional urea. It was concluded that Nanozeourea fertilizer application caused a highly significant increase in total nitrogen content that's why protein content increased.

8.2. Nano chitosan

Chitosan is the deacetylated form of chitin. It is the second abundantly available biopolymer on the planet (Kaya *et al*., 2014) [60]. Chemically, chitosan consists of glucosamine and N-acetyl glucosamine residues (Sashiwa and Aiba, 2004) [115].

Chitin and chitosan are economic polymers as they can be isolated from marine waste like crustaceans, the waste exoskeletons of crabs, shrimp, arthropods, and microorganisms such as fungus (Abdou *et al*., 2008) [3]. Corradini *et al*. (2010) [22] reported that chitosan biodegradable polymeric molecule has been used as a source to produce nitrogen, phosphorous and potassium based nanofertilizer.

They are composed of carbon (47.9-54.4%), oxygen (30.19-42.3%), nitrogen (5.8- 7.6%), and phosphorus (3.4- 6.1%). It can be used alone or mixed with metals like copper (Cu), silver (Ag), and zinc (Zn) to produce nanocomposites that enhance its biological and physicochemical properties. This effectiveness is attributed to chitosan's strong metalbinding affinity, due to the free amine groups in its polymeric structure (Curotto and Aros, 1993) [24]

The encapsulation of Zn enhanced the zeta potential value of the nanocomposite chitosan that consequently resulted in enhanced anti-bacterial activity (Saharan *et al.* 2016). Kaur *et al*. (2018) [59] reported that chitosan-zinc oxide nanocomposites (Ch-ZnO) were tested for their antifungal activity against Fusarium wilt in chickpeas. In addition to achieving approximate 40% reduction in disease, the use of Ch-ZnO also promoted the growth of chickpeas.

Elshamy *et al*. (2019) conducted a field experiment on application of nano chitosan NPK fertilizer on potato plant in Egypt. The crops were treated with distilled water (control), bulk NPK fertilizer, and nano Chitosan-NPK fertilizer at concentrations of 10%, 50%, and 100%. The results indicated that treatment with nanofertilizers significantly increased in the number of tubers plant^{-1}, tuber yield plant^{-1}, average tuber weight and dry weight of tubers plant^{-1} for tuber yield at harvest stage as compared with control. The result showed that highest values of N, P and K in shoots and tubers of potato plants were obtained by using nano Ch-NPK 10% as compared with other treatments. This study showed proved that excessive use of fertilizer to enhance the crops productivity does not necessarily contribute to yield enhancement.

Battikha *et al*. (2020) found that foliar spraying of chitosan nanoparticles fortified with 15% nano-nitrogen at 0.5-1.5 g L^{-1}, applied three times at three-week intervals, markedly improved faba bean growth and yield. Increasing the concentration progressively enhanced plant height, leaf and branch number, biomass accumulation, and pod and seed production, with the strongest response at 1.5 g L^{-1}. These effects were linked to the bioactive properties of chitosan, which modulate key physiological and molecular processes that stimulate vegetative development.

Turk *et al*. (2025) [136] evaluated the combined effects of nano-chitosan foliar sprays and Azotobacter root inoculation on hybrid kohlrabi grown in a desert production system. Foliar application of nano-chitosan at 0, 1, and 2 g L^{-1} was paired with root inoculation using 0, 5, or 10 g of Azotobacter. The strongest response occurred with 2 g L^{-1} nano-chitosan combined with 5 g Azotobacter, which significantly improved plant height (60 cm), leaf number (21.67), chlorophyll content (77.59 mg 100 g^{-1}), knob weight (278.9 g $plant^{-1}$), total yield (14.87 t ha^{-1}), as well as nitrogen (3.43%) and protein content (21.48%). This interaction treatment was consistently superior across all measured growth and yield traits.

Al-Malikshah and Abdulrasool (2025) [10,] evaluated the combined use of nano-chitosan loaded with NPK and botanical extracts (nettle and green tea) on potato yield and quality. The interaction of nano-chitosan-NPK at 15% with green tea extract at 4 g L^{-1} produced the strongest response, yielding the largest leaf area, the highest tuber yield per plant, and greater tuber dry matter. This combination also markedly increased the amino acids arginine and glutamine in the tubers, demonstrating its potential to enhance both productivity and nutritional quality.

8.3. Nano biochar

Nano biochar, formed through biomass pyrolysis, is a carbon rich material with a crystalline structure that improves soil conditions (Yan *et al.*, 2015). Nanobiochar, with its increased surface area, stability, and abundant functional groups, offers superior adsorption and reactivity compared to traditional biochar. Its higher surface-to-volume ratio and larger pore volumes enhance its adsorption capacity, making it more effective (Noreen and AbdElsalam, 2021) [86]. Enhanced negative zeta potentials, smaller hydrodynamic radius, and higher oxygen-carbon functional groups further boost its effectiveness (Ramanayaka *et al*., 2020) [101]. Various applications in agriculture including plant growth improvement, disease management, pesticide remediation, fertilization, soil amendment and supporting microbial growth. Also, it helps phytoremediation, energy production, mitigating global warming, and sequestering carbon (Helal *et al*., 2019) [48]. When nano biochar combined with acidic solutions, it releases elements like Si, Fe, S, P, K, Mg, and Ca into the soil, making them available for plant and microbial use (Hua *et al*., 2014) [51].

Mubashir *et al*. (2023) [79] found that foliar application of nano-biochar nutrient solution improved growth and biomass in tomato plants under drought stress. The 1% concentration significantly enhanced fresh biomass, leaf number, and shoot length, while the 5% concentration improved root length and fruit weight. Nano-biochar also mitigated drought induced oxidative stress by reducing ROS accumulation, lipid peroxidation, and enhancing membrane stability, demonstrating its potential to support plant growth under drought conditions.

Saini *et al*. (2025) [107] evaluated nitrogen-fortified nanobiochar (NBN) as a strategy to improve nitrogen-deficient soils while reducing dependence on mineral fertilizers. Across twelve treatments, the combined application of 75% mineral N with 5 kg ha^{-1} NBN (N75NBN5) produced the most favorable outcomes, enhancing soil moisture, infiltration, aggregate stability and hydraulic conductivity by roughly 1.0-1.4 times over N100 and N75 alone. This treatment also increased soil organic carbon and available N forms, boosted root biomass, length and volume, and raised rice yield by 26.8% relative to N75, whereas NBN1 showed the weakest performance. Strong correlations between yield and soil physical and chemical improvements confirmed NBN's role in enhancing nutrient uptake and crop growth. Overall, integrating NBN with reduced mineral N (N75NBN5) offers both agronomic and environmental benefits by improving soil function and utilizing agricultural waste as an effective amendment.

Sashidhar *et al*. (2025) [114] showed that converting rice husk biochar into its nanoform (NRB) and functionalizing its surface enables it to act as an effective slow-release carrier for micronutrients. Using zinc as a model nutrient, they found that Zn-functionalized nano-biochar (Zn-FRB) enhanced rice seedling growth more than NRB, increasing soluble protein content and reducing oxidative stress enzyme activity, indicating better protection against membrane damage. Zn-FRB also upregulated Zn-homeostasis and phloem-transporter genes, demonstrating improved micronutrient delivery and translocation. Overall, Zn-FRB outperformed NRB in promoting growth, minimizing oxidative damage, and enhancing Zn transport, highlighting its potential as a slow-release micronutrient system for crops.

9. Effect on seed germination

Ananda *et al*. (2019) [12] conducted a study to determine the influence of cuprous oxide nanoparticles (Cu_2O NPs) biosynthesized from leaf extracts of *Flacourtia montana* on the seed germination, seedling growth, and vigor index of tomato. The study found that the highest germination percentage (95%) was observed at a concentration of 20 ppm Cu2O NPs, which also promoted increased root shoot elongation and highest vigor index.

Nanoparticle applications can improve seed germination by increasing water uptake and retention. After a two-day incubation, tomato seeds exposed to carbon nanotubes showed a 19% higher moisture content compared with untreated seeds, demonstrating that CNTs notably enhance seed hydration (Agrawal *et al*., 2022) [5].

Prajapati (2022) [92] prepared and evaluated the effect of chitosan nanofertilizer on wheat seeds. Seeds were treated with various concentrations of chitosan nanofertilizer, controls, and other nutrients like bulk chitosan, urea, ZnSO4 and NiSO4, then incubated. Seed priming with chitosan nanofertilizer significantly promoted seed germination per cent and also also induced seedling vigor growth in wheat. Specifically, seeds treated with a 0.12% concentration of chitosan nanofertilizer were particularly effective in supporting crop resilience during stress conditions.

Ali *et al*. (2025) demonstrated that zinc plays a critical role in enzyme activation, hormone regulation, and stress tolerance, with optimal seed yield achieved when crops were planted in October and supplied with moderate ZnO levels (2.5 ppm). Higher ZnO (5 ppm) improved vegetative traits such as root length and plant height but contributed less to overall productivity. Multivariate analyses further showed distinct treatment-response patterns, while strong correlations between yield, germination rate, and node number emphasized key physiological drivers of productivity.

A field study in spring 2021 demonstrated that soaking seeds in nano-iron solutions (0-150 mg L^{-1}) significantly improved germination, field emergence, grain yield, yield components, and grain Fe content, with the strongest response observed at 150 mg L^{-1} (Hassan *et al*., 2025) [46].

Zec *et al*. (2025) [145] reported that foliar application of a calcium-based nanofertilizer containing Ca, Si, B, and Fe significantly improved fruit size, germination energy, final germination, seedling vigor, root growth, and biomass across seven tomato genotypes compared with conventional fertilizer and the control. Although shoot elongation and several fruit structural traits were largely genotype-dependent, the nanofertilizer consistently enhanced physiological performance, indicating its strong potential for boosting tomato yield and early seedling development.

A recent study examined hydrothermally synthesized nano-fertilizers derived from yeast extract and their influence on the germination and early growth of *Nigella sativa*. The treatments significantly accelerated germination; soaking seeds in 1 g L^{-1} yeast suspension reduced germination time from 18.10 to 14.71 days, while 1 mg L^{-1} nano-bread yeast extract further shortened it to 14.16 days (Al-Hatem *et al*., 2025) [7].

10. Effect on physical properties of soil

Shaban *et al*. (2021) [117] conducted a field experiment to investigate the effects of NPK nanofertilizers, biofertilizers, and humic acid on certain soil physical properties under saline conditions. The study found that NPK chitosan nanofertilizers significantly improved soil properties by increasing water-stable aggregates, enhancing hydraulic conductivity and porosity, and reducing bulk density, primarily due to the higher organic matter content provided by chitosan.

Sammar Raza *et al*. (2023) [111] evaluated nano-biochar (NBC), a finely engineered carbon material designed to enhance soil properties, as a soil amendment to improve wheat performance under drought stress. NBC applied at 1% markedly boosted antioxidant enzyme activities and plant height compared with other doses, while drought at critical stages especially grain filling caused major declines in growth and yield traits. Overall, NBC mitigated the negative impacts of salinity and moisture deficits and improved physiological traits, indicating its potential as a soil amendment for sustaining wheat productivity under limited water availability.

Tourajzadeh *et al*. (2024) [135] conducted a two-year greenhouse study using a factorial CRD to evaluate the effects of salinity (S_1: 1 dS m^{-1}, S_2: 4 dS m^{-1}, S_3: 7 dS m^{-1}), depth of irrigation water (I_1: 60%, I_2: 80%, I_3: 100% of plant water requirement) and nano-biochar (NB) (NB_1: 0%, NB_2: 2%, NB_3: 4%) on quinoa. Salinity (1-7 dS m^{-1}) and reduced irrigation (60-100% of crop water requirement) significantly depressed yield, but applying NB especially at 2% partially mitigated these stresses and improved traits such as spike weight, grain weight, and leaf area index. While 4% NB reduced proline and carbohydrate levels, moderate NB (2%) enhanced seed protein under 4 dS m^{-1} salinity and 80% irrigation. Water productivity was highest under $I_1NB_2S_1$ (12.51 kg m^{-3}) and lowest under $I_3NB_3S_3$. Overall, NB effectively reduced the negative impacts of salinity and drought, supporting improved growth and yield, and the authors suggest that quinoa can be irrigated with water up to 4 dS m^{-1} salinity when NB is used.

Rodrigues *et al*. (2025) [105] evaluated thermoplastic starch (TPS) reinforced with nanoclay (NC) and nano lignin (NL) as a sustainable soil conditioner. TPS nanocomposites containing 7% NC showed markedly improved swelling capacity and cation exchange properties, while the addition of 0.3% NL enhanced UV-C resistance and thermal stability. The TPS/NC 7%/NL 0.3% formulation demonstrated better soil water retention, efficient NPK absorption and controlled release, and reduced nutrient leaching, along with antimicrobial activity. Greenhouse tests with cherry tomato confirmed superior seedling growth using this nanocomposite, highlighting its potential as a biodegradable soil-conditioning material for sustainable agriculture.

Feizi *et al*. (2025) [34] evaluated a biodegradable soil stabilizer made from walnut shell-derived nanocellulose (WSNC) grafted onto a poly acrylic acid-co-acrylamide copolymer for controlling wind erosion in arid regions. Among the tested formulations, the 3% WSNC applied in two layers provided the best performance, showing markedly higher compressive strength, shear resistance, and complete suppression of wind erosion. Although increasing WSNC content did not further enhance crust thickness, the nanocomposite improved soil bonding and mechanical integrity. Overall, the WSNC-based binder offers an effective and environmentally friendly option for stabilizing sandy soils while repurposing agricultural waste.

11. Effect on stress mitigation

The soil application of nano-chitosan has proven highly effective for potatoes under drought, where a 50 mg L^{-1} guttation spray reduced transpiration by 20-30% and improved water-use efficiency by 15-25% at 50% soil moisture deficit (Geries *et al*., 2020) [37].

Bolhassani and Feizian (2025) [18] showed that nano-chitosan markedly improved the growth and physiological performance of marigold under salinity stress. Across four salinity levels (0-150 mM NaCl) and different modifier treatments, foliar application of 0.5 g L^{-1} nano-chitosan produced the highest plant biomass, flower number, leaf number, plant height, photosynthetic pigments, and leaf water content under non-stress conditions. In contrast, severe salinity (150 mM) without any modifier resulted in the poorest growth. Although salinity increased ion leakage and reduced leaf water content, nano-chitosan application alleviated these effects and enhanced stress tolerance. Proline accumulation was greatest under 150 mM NaCl combined with 0.5 g L^{-1} nano-chitosan, indicating an induced osmoprotective response. Overall, the study suggests that nano-chitosan is an effective foliar amendment for improving performance under saline conditions.

Munir *et al*. (2025) [80] demonstrated that foliar-applied nano-fertilizers can effectively enhance drought tolerance and maintain cluster bean productivity. Nano-K, nano-Zn, nano-B, and their combined application improved key agronomic and physiological traits by boosting photosynthesis, pod yield, seed weight, and protein content under reduced irrigation, confirming their value as an eco-friendly strategy for climate-resilient production.

Wei *et al*. (2025) showed that applying 100 mg kg^{-1} nano SiO_2 markedly improved soybean drought tolerance by enhancing silicon accumulation in shoots and roots, restoring ionic balance (40% reduction in Na^+/K^+ ratio), and lowering proline buildup by 35%. The treatment also boosted nitrogen-metabolism enzymes including nitrate reductase (NR) and glutamine synthetase (GS) by 25-30%, strengthened antioxidant defenses superoxide dismutase up by 15%, reduced oxidative stress markers (H_2O_2 and malondialdehyde down 20-25%), and increased pod number and grain weight by 15% and 20%, respectively, demonstrating the strong potential of nano SiO_2 as a sustainable strategy to maintain soybean productivity under drought.

Nano-biochar has emerged as a multifunctional sorbent capable of improving soil conditions, enhancing plant productivity, and supporting sustainable agriculture. Shahzadi *et al*. (2025) [118] showed that foliar application of a nanobiochar (NB) colloidal solution (0-5%) markedly improved growth and stress tolerance in tomato plants under both normal and saline (60 mM) conditions. The 3% NB treatment delivered the strongest effects, increasing plant height, biomass, fruit number and weight, enhancing chlorophyll and carotenoid levels, boosting leaf water content, and elevating primary and secondary metabolites. It also stabilized cell membranes by lowering electrolyte leakage and lipid peroxidation.

Jayasudha *et al.* (2025) [55] evaluated Nano DAP and hydrogel amendments for improving soil quality and tomato productivity under drought conditions.The combined application of Nano DAP and hydrogel produced the most notable improvements, significantly increasing soil water-holding capacity, reducing bulk density, and enhancing soil nitrogen and organic carbon levels. This treatment also stimulated microbial activity, improving micronutrient availability and overall plant performance. The findings highlight Nano DAP-hydrogel combinations as a promising strategy for mitigating drought stress and promoting sustainable tomato production in arid regions.

12. Effect on soil nutrient status

Panda *et al.* (2020) [87] studied on the effects of nano fertilizers on tomato yield, yield attributes, and economic outcomes (variety Utkal Pallavi) in Odisha demonstrated significant variations in soil nutrient content across different treatments are T_1 to T_3- Nano-Max NPK at 3,4,5 ml L^{-1} + RDF, T_4 to T_6- Pramukh at 3,4,5 g L^{-1} + RDF, T_7- Nano-Max NPK at 4 ml L^{-1} + Pramukh at 4 g L^{-1} + RDF and T_8- control with only RDF. RDF is 125 kg N: 60 kg P2O5: 100 kg K2O ha^{-1}. The treatment with Nano-Max NPK (3ml L^{-1}) and RDF led to elevated levels of available phosphorus and potassium content of 31.96 kg ha^{-1} and 112.7 kg ha^{-1}, respectively.

Rashid *et al.* (2023) [102] developed nanobiochar (nanoB) from goat manure and evaluated its use alone or combined with CuO nanoparticles (nanoCu) in wheat-grown clay loam soil. While nanoCu mainly increased soil and plant Cu levels, nanoB significantly improved microbial biomass N, mineral N, and available P, and these effects were further enhanced when nanoB and nanoCu were applied together. The combined treatment produced substantial gains in wheat biomass, grain yield, and N and Cu uptake compared to all other treatments. Overall, nanoB, either alone or mixed with nanoCu enhanced soil microbial activity, nutrient availability, and crop productivity, making the nanoB + nanoCu blend a promising option for improving soil quality and micronutrient uptake.

In a split-plot experiment, foliar spraying nano-urea at 2 mL L^{-1} produced the highest soil nutrient availability, with nitrogen, phosphorus, and potassium reaching 194.41, 54.48, and 152.48 kg ha^{-1}, respectively, across treatments involving varying doses of conventional fertilizers and nano-urea/nano-DAP applications (Sajjan *et al.*, 2025) [108].

Pandey *et al.* (2025) [88] conducted an experiment on blackgram (*Vigna mungo*) evaluated six fertilization treatments, including a full 100% RDF (25:50:30 N:P:K kg ha^{-1}). Treatments combined different proportions of recommended fertilizers with foliar sprays of Nano Urea (4 ml L^{-1}) and Nano DAP (10 ml L^{-1}). Notably, the treatment receiving 50% of recommended N and P with 100% K plus two foliar sprays of Nano Urea and Nano DAP produced the most favorable results, showing marked improvements in soil fertility status, including higher available nutrient levels, alongside significant gains in crop nutrient content, nutrient uptake, and grain yield.

A pot experiment on $KMnO_4$-N-deficient soil showed that the slow-release nitrogen nano clay polymer composite (N-NCPC) maintained markedly higher soil mineral N—$KMnO_4$-N, nitrate, and ammonium—than neem-coated urea or nano urea, with the 100% RDN dose recording the highest values. N-NCPC also preserved key hydrolysable N fractions at levels comparable to neem-coated urea and significantly enhanced soil enzyme activities, while nano urea reduced these fractions. The 50% RDN dose of N-NCPC achieved the highest apparent N recovery (74.4%), indicating that N-NCPC can maintain soil nutrient pools and nitrogen-use efficiency even at reduced N inputs, offering a potential 50% substitution of conventional nitrogen fertilizers without compromising soil fertility or yield (Ray *et al.*, 2025) [103].

13. Effect on crop growth and yield

The study by Abdel-Aziz *et al.* (2016) [2] demonstrated that Nano 10% NPK fertilizer significantly outperformed higher nano and traditional NPK concentrations in improving wheat yield on Egypt's sandy soils, highlighting nanoparticles' efficiency at lower concentrations.

A field study conducted to compare foliar sprays of different nano-fertilizers (di-spray N+P, N+K, P+K; tri-spray N+P+K; and Super Micro Plus, SMP) with conventional NPK+TE fertilizer and an untreated control in wheat. Among all treatments, the SMP nano-fertilizer delivered the highest performance, producing a grain yield of 5.996 Mg ha^{-1}, protein content of 13.69%, a harvest index of 44.96%, and the greatest fertilizer productivity (1,936 kg kg^{-1}). These values clearly exceeded those of the control (4.060 Mg ha^{-1}, 11.94%, 35.27%) and the traditional fertilizer (5.198 Mg ha^{-1}, 11.94%, 569 kg kg^{-1}). Significant enhancements were also recorded in plant height (87.77 cm), spike length (12.22 cm), and chlorophyll level (58.22 SPAD) (Al-Juthery *et al.*, 2018) [9].

Lekshmi *et al.* (2022) [65] conducted an experiment to study the effect of nano fertilizer in the growth yield and quality of okra (*Abelmoschus esculenthus*). The treatment includes different combination of nanofertilizers. The RDF of Okra is 110: 35: 70 kg ha^{-1}. RDF of nano liquid formulation (NPK) is 4 ml L^{-1} and nano granular formulation (P&K) is 15 - 20 kg $acre^{-1}$. The result obtained with 50% NPK through soil application along with 50% N and 50% PK through foliar application of nanofertilizer was recorded the best among in all combination of conventional fertilizer NPK and nano NPK in term of growth and yield attribute (days to first harvesting 46.97, pod length 12.72 cm, pod width 1.65cm, number of pods per plant 29.23, average of pod weight 12.67 g, pod yield per plant 370.39 g, pod yield per plot 8.89 kg, pod yield 131.69 q ha^{-1}).

Thomas *et al.* (2022) [134] conducted a study to assess the effect of nano-nitrogen, supplemented with potassium on the growth and yield attributes of rice. The treatments differ in basal nitrogen dose (100%, 75%, 50%, 25%) and nano nitrogen top dressing at active tillering (AT) and/or panicle initiation (PI), with or without K2SO4; one treatment followed KAU POP, 2016. Productive tillers per m^{-2}, grain yield per hectare and straw yield per hectare were found to be superior in the treatment 50% basal RDN and top dressing with nano-nitrogen at AT along with K2SO4 at PI.

Saleemali *et al.* (2023) [110] conducted a field experiment in a well-established mulberry garden with the V-1 variety investigated the effects of nanofertilizers applied through foliar spray at 35 and 45 days after pruning. The analysis demonstrated that nanofertilizer application significantly enhanced mulberry growth and yield. Among the treatments, nano 19:19:19 at 6 g L-1 was the most effective, resulting in the longest shoot length (126.60 cm), the highest number of leaves per shoot (26.83), the largest leaf area (144.78 cm^2), the greatest hundred leaf weight (245.59 g), and the highest leaf yield (747.94 g $plant^{-1}$).

An experiment was conducted by Nandy *et al*. (2023) [84] to study the effect of integrated nutrient management along with foliar spray of nano zinc on yield of rice. The treatments were a control, various combinations of 100%, 75%, and 50% recommended nitrogen (RDN) from commercial fertilizer and 25% and 50% RDN from FYM, with or without nano zinc spray. It was found that maximum grain and straw yield were recorded with the application of 75% RDN from chemical fertilizer and 25% RDN from FYM along with nano zinc spray.

A study carried out to investigate its growth and yield responses to foliar applications of nano nitrogen (nN) and zinc (nZn) alongside conventional urea and ZnSO4 in chilli. The experiment comprised combinations of recommended doses of nitrogen (RDN) (75, 100 & 125%) along with two foliar sources, nano (nN and nZn at 0.4%) and conventional (urea at 2% and ZnSO4 at 0.2%) against control. Foliar application of nN and nZn at 0.4% + 125% RDN improved growth, yield attributes and green chili yield (33.07 t ha−1), compared to RDF (23.8 t ha−1) and conventional sources (30.9 t ha−1). Also, there was a substantial enhancement of 39.0% in yield (Sunil *et al*., 2024) [131].

Gopika *et al*. (2024) [41] conducted a field experiment to assess the influence of tillage practices and nano nitrogen on the yield and quality in chinese potato on sandy clay loam soil of Vellayani, Thiruvananthapuram. The experiment was laid out in split plot design with three replications. The main plot treatments included conventional tillage, reduced tillage (RT) with surface incorporation of green manure cowpea and RT with surface retention of green manure cowpea and the sub plot treatments, different doses of nitrogen along with foliar spray of nano urea at 0.4 percent concentration. Foliar spray of nano urea @ 4 ml L-1 was given twice, at 20 and 40 DAP (days after planting). Nitrogen, P2O5 and K2O at the rate of 60:60:100 ka ha^{-1} formed the recommended dose of nutrients. The results revealed that the significant influence of reduced tillage and nano urea individually on tuber yield while among the combinations, RT + in situ green manuring and nano urea spray + RDF was found to yield comparatively better.

A field experiment was conducted by Maloth *et al*. (2024) [70] focused on the impact of using nano DAP through foliar application on plant growth, yield, enzymatic activity and nutrient content in paddy variety KNM 1638. The study recorded various growth parameters, enzymatic activity, yield and nutrient content. The treatments range from 100% NPK to varying combinations of NK and P with one or two nano DAP foliar sprays. The recommended fertilizer application was 150:60:40 kg ha^{-1} of N, P2O5 and K2O. The results demonstrated that, application of 100% NK + 75% P in combination with two foliar sprays of nano DAP at both tillering and panicle initiation stages led to superior plant growth parameters such as number of tillers hill-1 (13.18), total dry matter (42.12 g hill-1), increased yield parameters such as number of productive tillers hill-1 (11.25), number of grains panicle1 (297) and yield (7530.86 kg ha^{-1}).

Priyadarsini *et al*. (2024) [95] conducted a study to assess the growth and yield of cowpea variety Anaswara under different fertilizer and seed treatments. The treatments included fertilizer applications by nano NPK at 2/3, 1/2, 1/3, and 1/4 of the recommended dose, NPK as per POP (20:30:10 kg ha^{-1}), and an absolute control. The application of nano NPK (2/3 POP) significantly improved plant height (52.87 cm), number of branches (6), and dry matter content per plant (25.40 g). The highest pod weight per plant was recorded with nano NPK (2/3 POP) at 33.80 g, comparable to nano NPK (1/4 POP) at 32.29 g. The highest grain yield was achieved with nano NPK (2/3 POP) at 611.87 kg ha^{-1}, significantly higher than the control at 258.25 kg ha^{-1}.

Foliar application of green-synthesized NPK nano-fertilizers (2000-4000 mg L^{-1}) significantly improved vegetative growth, mineral content, fruit traits, yield, and oil quality of 'Picual' olives, with the 4000 mg L^{-1} dose showing the strongest response. Although phenolic compounds in the oil decreased slightly, all samples remained extra-virgin, and NPKNF treatments also enhanced flowering and fruit set in the following "off-year," reducing alternate bearing severity by increasing new shoot formation (Hmmam *et al*., 2025) [50].

Alenezi *et al*. (2025) [6] reported that applying NP nanofertilizer at 5-15% combined with bacterial and fungal biofertilizers significantly enhanced potato growth and yield, improving plant height, chlorophyll content, branching, biomass, leaf area, and total and marketable yield. The best vegetative performance was achieved with NP nanofertilizer plus microbial inoculants, while the highest yield (64.56 and 54.09 Mg ha^{-1}) occurred with 100% recommended NP fertilizer combined with both bacterial and fungal biofertilizers.

Application of conventional fertilizers at different nitrogen levels, with and without nano-urea, was evaluated in rainfed maize under semi-arid Indian conditions. The combined use of 100% RDN with nano-urea produced the highest yield and economic returns, while the 75% RDN + nano-urea treatment achieved a comparable yield, indicating that nano-urea sprays can reduce nitrogen use by 25% without compromising productivity and simultaneously lower GHG emissions and energy use, supporting its role in sustainable maize production (Gopinath *et al*., 2025) [42].

A two-year field study evaluated different application methods of nano-nitrogen and nano-zinc (seed treatment, root dipping, soil and foliar application) under conventional puddled rice and the System of Rice Intensification (SRI). The treatment combining 75% N with two foliar sprays of nano-N and nano-Zn at 25-30 and 45-50 DAT under SRI produced the highest improvements in growth, yield, grain and straw productivity, and quality traits. Strong positive correlations were observed among most parameters, and stepwise regression confirmed that grain and straw yields were largely driven by key growth, yield, and quality variables (Theerthana *et al*., 2025) [133].

A Rabi-season field trial demonstrated that applying 75% RDN + PK with nano-urea sprays at 40 and 60 DAS markedly improved wheat growth and yield, performing on par with the full 100% RDF. This treatment produced the highest grain, straw, and biological yield, indicating that nano-urea can maintain productivity while reducing nitrogen inputs, offering a more efficient alternative to conventional fertilization (Priyanshi *et al*., 2025) [96].

Huq *et al*. (2025) [52] investigated the influence of nano-nutrient foliar sprays on finger millet and reported that applying nano-N and nano-Zn along with 100% RDN + PK markedly improved growth, yield, grain quality, antioxidant activity, and nutrient-use efficiency compared with conventional fertilizers. Their best treatment produced the highest grain (3486 kg ha^{-1}) and straw yields (4810 kg ha^{-1}), along with superior ear head traits and economic returns, confirming nano-nutrient foliar feeding as a more efficient and cost-effective option for dryland finger millet cultivation.

14. Effect on nutrient uptake and nutrient use efficiency

Zeolite-based nanofertilizers provide controlled and prolonged nitrogen release. NH_4^+ held within zeolite channels is released gradually, improving crop uptake and dry matter production (Millán *et al*., 2008).

Gunaratne *et al*. (2016) [43] demonstrated that macronutrient delivery especially nitrogen is highly inefficient in conventional fertilizers due to substantial losses, and nanotechnology offers a viable solution to improve nutrient use efficiency. They synthesized urea-coated hydroxyapatite (UHA) and potassium-loaded nanocomposites using montmorillonite and *Gliricidia sepium* wood cavities, and found that both nanoformulations showed markedly slower nutrient release and significantly higher plant uptake over 60 weeks compared to conventional fertilizers, confirming their potential to enhance long-term nutrient use efficiency.

Amrutha (2019) [11] conducted a field experiment at the Regional Rice Research Station (RARS), Pilicode. The study aimed to examine the impact of soil and the foliar application of nano NPK fertilizers in comparison with conventional fertilizers on N, P and K uptake of chilli. The results indicated that nano NPK granule with a 19:19:19 foliar spray at 0.5% significantly outperformed other treatments in NPK uptake.

Nibin (2019) [85] reported that combined application of granular organic nano NPK at 12.5 kg ha^{-1} with foliar application of liquid nano NPK 0.4% attained maximum nutrient use efficiency in both okra and amaranthus. This may be due to the controlled release of nutrients from nanoformulation by preventing nutrient ions get fixed or lost to the environment.

Khan *et al*. (2021) [62] developed a macronutrient-loaded slow-release nanofertilizer using nanozeolite as the carrier, synthesized through a simple chemical method and characterized. Application of this nanozeolite composite fertilizer (NZCF) markedly improved soil water retention, swelling capacity, and nutrient release patterns compared to commercial fertilizers, resulting in a more controlled and prolonged nutrient supply. NZCF significantly enhanced lettuce growth parameters such as plant height and leaf/branch number and demonstrated superior nutrient use efficiency by sustaining nutrient availability over time, highlighting its potential as an environmentally friendly alternative to conventional fertilizers.

Deo *et al*. (2022) [27] conducted a field experiment to investigate the impact of nano-DAP on nutrient use efficiency in rice. The RDF is N, P2O5 and K2O was 100:80:60 kg ha^{-1}. The results showed that the treatment with 50% P, 100% N and K, root dipping, and two foliar sprays of nano DAP at 20-25 and 45-50 DAT resulted in the highest grain and straw yields. It enhanced nutrient uptake and nutrient use efficiency by 70.1% in N, 59.9% in P and 180.7% in K.

A study by Poudel *et al*. (2023) [91] found that foliar applications of nano P significantly improved nutrient uptake and yield. Specifically, applying 100% nitrogen and potassium (NK) with 75% phosphorus (P) and two foliar sprays of nano P increased grain yield by 37.1% compared RDF. This treatment also enhanced micronutrient uptake, with the highest levels of Cu, Mn, Zn, and Fe observed. Soliman *et al*. (2016) [126] reported that increased phosphorus intake is associated with higher nitrogen uptake.

Rajeshwari (2024) [99] conducted a field experiment to investigate effect of nano DAP and urea on growth, yield and quality of chilli. Treatments include nano DAP spray (NDS) and nano urea spray (NUS) each of 2, 4 and 6ml concentration with 50, 75 and 100 per cent of recommended dose of nitrogen and phosphorus (RNP). The recommended dose of fertilizer is 150: 75: 75 kg ha^{-1}. The treatment with 6 ml nano DAP and urea along with 100% RNP, recorded the highest nutrient uptake.

The sulfur nanoparticle-coated urea (SNPCU) formulations markedly improved nutrient dynamics in both rice and wheat by enhancing nitrogen uptake and nutrient use efficiency (NUE). Across all tested doses, SNPCU increased N uptake reaching gains of 70% or more and substantially boosted nitrogen recovery efficiency, rising by 34% and 26% in wheat varieties and 36% and 30% in rice varieties. SNPCU also suppressed urease activity by up to 52%, extending N availability in the soil and thereby improving NUE for up to 15 days, demonstrating its strong potential to reduce N losses while sustaining crop demand (Fraz *et al*., 2025) [35].

Shoukat *et al*. (2025) [120] reported that zinc and silicon nanofertilizers significantly improved maize growth, nutrient uptake, and yield under both saline and non-saline conditions, with nano-Si boosting biomass by 110% and nutrient-use efficiency by over 100%, and combined nano-Zn/Si increasing grain yield by 66-106% compared to the control. Their PCA analysis further confirmed strong associations between nano-Zn/Si treatments and key physiological and yield traits, highlighting their potential to mitigate salinity stress and enhance productivity in salt-affected soils.

15. Effect on quality of crops

Siva and Benita (2016) [122] aimed to prepare water-soluble iron nanoparticles and examine their effects on starch, photosynthetic pigments, phenolic, and iron content in ginger plants. Iron oxide nanoparticle application resulted in increased starch, chlorophyll, carotenoid, and phenolic levels compared to Fe-EDTA and control groups. The control plants showed chlorotic leaves, indicating iron deficiency. Iron content in rhizomes significantly increased with nano iron oxide treatment. These findings suggest that ferric oxide nanoparticles enhance ginger plants' nutritional quality, potentially aiding biofortification to address iron deficiency anemia.

Sreelaja (2018) [127] studied ginger quality enhancement using nano NPK fertilizers and organic management. Nano NPK was applied as a 0.5% foliar spray and as granules at 25 kg ha^{-1}. The combination of granules and foliar spray led to the highest levels of volatile oil, oleoresin, and crude fiber, attributed to improved nutrient use efficiency from frequent applications.

Starch and nitrate contents are the key indicators of potato tuber quality responded distinctly to nano and non-nano NPK applications. Among all treatments, foliar-applied 100% NPK nanofertilizer produced the highest starch content (81.34%), statistically matching the performance of foliar 50% nano NPK and foliar 100% non-nano NPK. In contrast, soil-applied treatments, particularly 100% non-nano NPK and 100% nano NPK, resulted in markedly higher nitrate accumulation in tubers, whereas foliar nano-based treatments consistently maintained lower nitrate concentrations. These findings highlight a clear quality advantage for foliar nano-NPK treatments by enhancing starch while limiting nitrate buildup compared to soil-applied formulations (Abd El-Azeim *et al*., 2020) [1].

Modi *et al*. (2021) [78] studied on greenhouse cucumber cultivar KPCH-1 examined the effects of NPK nanofertilizers on nutrient recovery. The treatments were 100% RDF (90:75:75 kg ha^{-1}) via water-soluble fertilizer (WSF), and 60%, 50%, 40%, and 30% RDF as nano-fertilizers, along with an absolute control. The 40% RDF nano-fertilizer treatment led to the highest nutrient recovery efficiency for nitrogen, phosphorous and potassium, demonstrating superior nutrient uptake and overall plant performance.

Deepa *et al*. (2022) [26] studied the impact of soil application of organic nano NPK on banana cv. Nendran. Applying 45 g per plant in 6 splits yielded the highest levels of total sugars

(19.94%), reducing sugars (15.17%), total carotenoids (303.67 mg 100 g^{-1}), sugaracid ratio (63.92), ascorbic acid (2.2%), and moisture content (24.95%).

Mahdavi *et al*. (2022) [67] found that soil treated with 500 mg kg^{-1} of nano Zn chelate, the highest Zn availability, total phenol and soluble sugar levels, berry anthocyanin, flavonoid, titratable acid, catalase, and guaiacol peroxidase activity, as well as protein, ascorbic acid, iron, and potassium content and yield in grapevine was observed.

16. Effect in B:C Ratio

Srishti (2022) [128] investigated about response of coriander to foliar application of fertilizers and nanofertilizers. The treatments include foliar sprays of urea (1.5%, 2.0%), nano urea (0.20%, 0.25%), zinc (0.20%, 0.40%), nano zinc (0.02%, 0.04%), magnesium (0.40%, 0.60%), nano magnesium (0.04%, 0.06%), and a control. The present study suggested that the highest gross income, net monetary return and the B:C were observed in the treatment sprayed with 0.25% nano urea. The lowest gross income, net monetary return and B:C were observed in foliar spray of 0.60% magnesium.

An experiment was carried out by Sruthi *et al*. (2022) [129] to investigate the profitability in sesame cultivation due to soil application of organic nano NPK. The treatments consisted of 2 levels of organic nano NPK (25 kg/ha and 50 kg/ha) with FYM and without FYM, soil test based recommendation of NPK and FYM along with absolute control. It was found that the soil application of organic nano NPK 50 kg/ha and FYM 5t/ha had significantly produced higher seed yield (712.5 kg/ha). Subsequently, higher gross returns (Rs. 2,13,750/-), net returns (Rs. 1,06,554/-) and BC ratio (1.99) for sesame was obtained for T_6.

Kanjilal *et al*. (2023) [57] conducted a field to evaluated the performance of green gram (*Vigna radiata* L. Wilczek) under single super phosphate (SSP) and nano phosphorus treatments. The result indicated that foliar application of 2 ml L^{-1} of nano phosphorus at 15 DAS resulted in 33.13% increase in grain yield and a 50.28% higher profit compared to the application of 100% phosphorus through SSP. It demonstrated that the highest net return of Rs. 37,447.71 per hectare was achieved with the foliar application of nano phosphorus at 2 ml L^{-1} at 15 days after sowing (DAS). The highest benefit-cost (B:C) ratio of 1.35 was attributed to the higher seed yield and proportionately greater gross return compared to the total cost of cultivation.

Gopinath *et al*. (2025) [42] showed that applying 100% NPK with nano-urea (N100PK + nano-urea) produced the highest economic returns in rainfed maize, while N75PK + nano-urea achieved comparable yields and profitability**,** demonstrating that nano-urea can cut nitrogen use by 25% without economic loss. This reduction translates into a potential national saving of 9.6 million tons of urea and USD 3.4 billion in subsidy costs**,** highlighting nano-urea as a financially efficient and scalable strategy for sustainable maize production.

17. Effect on microbial population

Meena *et al*. (2021) [76] investigated the effect of foliar application of nanofertilizers (P, K, and Zn) on soil microbial properties in the sub-humid southern plains of Rajasthan. The treatments comprising foliar application of different doses of nano P, K, and Zn, along with RDF and a control, significantly affected microbial population (bacteria and fungi) and microbial biomass-C. Nano P and K were applied at 80 ml L^{-1} water while Nano Zn at 20 ml L^{-1} water as per scheduled treatments. The maximum microbial population (bacteria and fungi) and microbial biomass-C were observed in two spray of nano P at 14 and 28 DAS, along with 100% RDF. Moreover, the foliar application of nanofertilizers, particularly nano P, stimulated microbial growth by providing nutrients and directly increased their population in the soil.

Kondal *et al*. (2021) [63] demonstrated that nano-chitosan-urea composite (NCUC) markedly altered soil microbial N dynamics compared with conventional urea. NCUC enhanced dehydrogenase activity and soil organic carbon while lowering urease activity, NH_4^+-N and NO_3^--N levels due to slower urea hydrolysis. This reduced the abundance of ammonia-oxidizing bacteria (AOB) and archaea (AOA), indicating a strong microbial regulatory effect on N transformation pathways. Overall, the nano-polymer formulation reshaped key microbial communities involved in nitrification, supporting its potential as a slow-release N source.

Chen *et al*. (2024) [21] demonstrated that applying nanocarbon (NC) and nano-calcium carbonate (NCC) alongside conventional fertilizers markedly improved the rhizosphere microenvironment of wheat, as reflected by higher soil enzyme activities (urease, catalase, alkaline phosphatase, and sucrase) and increased fungal, bacterial, and actinomycete populations. Both full-rate (100% CF + 50% NC + 50% NCC) and reduced-rate (70% CF + 35% NC + 35% NCC) composite nanofertilizers enhanced microbial diversity and boosted the abundance of beneficial taxa such as Proteobacteria, Bacteroidetes, and Actinobacteria, all of which were strongly associated with improved soil biochemical functioning and nutrient cycling.

Gao *et al*. (2025) [36] showed that nano calcium carbonate (NCC) significantly modified soil P dynamics by enhancing microbial functional groups and enzymatic activity linked to P cycling. NCC, particularly at 0.30% and 0.45%, increased soil available P and alkaline phosphatase activity while enriching beneficial P-solubilizing and mineralizing bacterial taxa such as Actinobacteria, Acidobacteria, Haliangium, and Gemmatimonas, alongside higher abundances of key P-cycling genes (ppx, ppa, phoD, gcd). These shifts accelerated organic P mineralization and inorganic P solubilization, ultimately improving P concentrations in wheat tissues and enhancing overall P uptake efficiency.

Upadhyay *et al*. (2025) [137] showed that combining 75% of the recommended nitrogen with full PK and foliar nano-urea with or without nano-zinc maintained crop nutrient uptake and soil biological functioning at levels comparable to full RDF. Treatments with nano-fertilizers sustained dehydrogenase activity similar to RDF and promoted a shift toward beneficial microbial groups such as Actinobacteriota, indicating improved microbial activity and nutrient cycling. This enhanced microbial community structure and enzymatic activity supported efficient nutrient uptake, demonstrating that nano-fertilizer integration can sustain soil biological health while reducing nitrogen inputs.

Application of nano-boron nitride (nano-BN) markedly altered rhizosphere microbial dynamics, increasing dissolved organic substrates that stimulated beneficial microbial activity and enriched taxa involved in carbon and nitrogen cycling. Nano-BN also upregulated key functional genes linked to fermentation and nitrogen fixation, promoting microbial groups such as *Phenylobacterium*, *Novosphingobium*, and *Reyranella*, indicating its strong potential to enhance soil microbial functioning while supplying boron sustainably (Xu *et al*., 2025) [142].

18. Effect on biofortification

Durgude *et al*. (2022) [40] demonstrated that foliar application of mesoporous nanosilica and reduced graphene oxide-based Fe and Zn nanocomposites markedly improved nutrient uptake and use efficiency in rice, with Zn and Fe uptake at 60 DAT and at harvest significantly higher than conventional fertilization. Notably, applying 30 ppm Zn and 5 ppm Fe through these nanocomposites enhanced rice grain yield by 53% and increased Zn and Fe use efficiency by 527% and 380%, respectively, underscoring their strong potential for crop biofortification and efficient micronutrient delivery.

Twice-foliar application of 60 ppm Zn + 30 ppm Fe through mesoporous nanosilica (mNs) and 40 ppm Zn + 20 ppm Fe through reduced graphene oxide (rGO) produced significantly higher economic and biological yields of cabbage and cauliflower than conventional fertilization. Increasing nano-Zn and Fe doses via mNs enhanced nutrient content and uptake, whereas higher doses delivered through rGO reduced nutrient accumulation. Overall, both the treatments were the most effective treatments, producing Fe- and Zn-enriched biomass with higher protein and phenol content, while soil available Zn and Fe remained unchanged (Himani *et al*., 2022) [49].

Salcido-Martínez *et al*. (2023) [109] conducted a study aimed at evaluating yield and increasing the magnesium content in the fruits of green beans cv. 'Strike' through the application of Mg-nanofertilizer. The experiment included two Mg sources are Mg nanofertilizer (nano Mg) and MgSO4, applied at doses of 50, 100, and 200 ppm, along with a control group. The most efficient treatment in enhancing Mg content in the fruit was nano Mg at 200 ppm, which resulted in a biofortification level exceeding 120% relative to the control.

Yuvaraj *et al*. (2023) [144] found that zinc oxide nanoparticles (ZnO NPs) significantly outperform zinc sulfate ($ZnSO_4$) in increasing zinc content in rice grains grown in Zn deficient soil. Specifically, ZnO NPs led to higher zinc concentrations in whole grain (20.5 mg Zn kg^{-1}), de-husked grain (16.2 mg Zn kg^{-1}), and polished grain (13.5 mg Zn kg^{-1}) compared to $ZnSO_4$, which resulted in lower concentrations (15.2 mg Zn kg^{-1}, 11.9 mg Zn kg^{-1}, and 9.7 mg Zn kg^{-1} respectively). This suggests ZnO NPs could be a valuable tool for enhancing the nutritional quality of rice and tackling zinc deficiencies in populations heavily dependent on rice.

Sekaran and Singaravel (2023) [116] examined the effect of biochar and zeolite-based Zn and Fe nanocomposites on rice growth, yield, and micronutrient enrichment using a pot experiment. Among the seven treatments, the combination of the recommended fertilizer dose with nano-biochar composite (1 g kg^{-1}) plus foliar nano-ZnO and nano-FeO (500 ppm) produced the strongest response, significantly improving growth and yield and achieving grain and straw yields of 27.7 g pot^{-1} and 42.1 g pot^{-1}, respectively. This treatment also resulted in the highest grain Zn (23.5 mg kg^{-1}) and Fe (225 mg kg^{-1}) concentrations, demonstrating its effectiveness for Zn-Fe biofortification.

19. Advantages of nanofertilizer

Nanofertilizers offer multiple advantages for modern agriculture, primarily due to their nanoscale size and high reactivity. They are highly soluble, enabling rapid plant absorption, and significantly enhance nutrient-use efficiency by improving cellular penetration and targeted nutrient delivery (Solanki *et al*., 2015) [125]. Their sustained-release behavior reduces the frequency of application and lowers the total amount of chemical fertilizers required, leading to higher crop yields and improved food quality while minimizing environmental contamination. Because they reduce input costs and enhance productivity, nanofertilizers can also increase farmers' income. Additionally, their concentrated form makes them easy to store, handle, and transport, further supporting their practical use in sustainable farming systems (Solanki *et al*., 2015; Mishra *et al*., 2021) [125, 77].

20. Disadvantages of nano fertilizer

Nanofertilizers also come with several drawbacks that limit their widespread adoption. High concentrations of nanoparticles can be toxic to plants and beneficial soil microorganisms, disrupting nutrient uptake and soil fertility (Kah & Hofmann, 2014; Nair & Chung, 2017) [56, 81], although low doses such as 50 mg L^{-1} may still provide benefits (Reddy *et al*., 2016) [104], and FDA evaluations indicate no direct risk to human health from approved nano-products (Bahadar *et al*., 2016) [16]. Environmental persistence is another concern, as nanoparticles may accumulate in soil and ecosystems over time (Simononin & Rachaume, 2015). Production costs and technical challenges also make nanofertilizers less accessible, slowing large-scale implementation (Bindraban *et al*., 2015) [17]. Furthermore, the long-term effects of nanoparticle exposure on human health remain uncertain, emphasizing the need for expanded nano-toxicology research to establish safe, context-specific application guidelines (DeRosa *et al*., 2010; Oberdörster *et al*., 2005). Plants exposed to high concentrations of ZnO NPs had their roots obstructed, which led to a decrease in the uptake of other supplements and a loss of macro- or micronutrients (Nair & Chung, 2017) [81].

21. Conclusion

Nutrients present in the bulk chemical forms as delivered by conventional fertilizers are not fully accessible to plants. In addition, the utilization of most of the macronutrient is very low due to their inversion to insoluble form in soil. Keeping in mind the damage caused by the excessive application of conventional fertilizers to the environment, it is necessary to consider an environmentally friendly approach. Nanotechnology will have a great impact on agriculture science. Nanoscale or nanostructured materials as fertilizer carrier or controlled release vectors for building of the so-called smart fertilizers. Nanofertilizers improve the fertility of the soil by reducing the nutrient losses and thereby increasing the nutrient use efficiency. It also helps in minimizing the potential negative effects associated with over dosage and enhances the crop production with added benefits of sustainability.

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