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REVIEW ARTICLE

Nanofertilizers: Insights and confronting challenges in sustainable crop production

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Abstract

Use of chemical fertilizers has become significantly important for enhancing crop productivity and profitability. The chemical fertilizers, though prove very useful in improving growth and yield of crops, but exert harmful to the environment and human health. With an ever-growing demand for food production amidst environmental challenges and resource constraints, the exploration of innovative alternative solutions has become essential. Nanofertilizers are promising alternatives to traditional fertilizers. The cost-effectiveness, eco-friendliness, non-toxicity and increased stability make nanofertilizers more effective than chemical fertilizers. Nanofertilizers can play an important role in achieving sustainability in agriculture by precisely delivering and releasing nutrients using nanoscale active substances in a controlled manner. This also reduces the leaching of nutrients into groundwater. Additionally, nanofertilizers have the potential to improve tolerance to environmental stresses when applied in combination with microorganisms. The present review provides information related to types of nanofertilizers, mechanisms of their interaction in soil and plants, role of using nanofertilizers in improving crop productivity and nutrient management. The challenges and risks of using nanofertilizers, such as their safety for living things, impact on the environment and cost-effectiveness have been also discussed. This review aims to share knowledge about sustainable farming and provide information about benefits and challenges of using nanotechnology in crop production.

Keywords

carbon nanotubes (CNTs); chitosan-based nanofertilizers (CBNFs); controlled-release nanofertilizers (CRNFs); slow-release nanofertilizers (SRNFs)

Introduction

Increasing food production to meet the demands of a growing population remains one of the most significant global challenges faced by humans today. Studies have predicted that the global population will reach about 9.7 billion by 2050, necessitating a rise in food production from 60 to 100 % (1). Agriculture has relied on chemical fertilizers, development of disease-resistant crops and genetically modified varieties over the past 50 years. Fertilizers contribute to about one-third of crop yields, but their efficiency is only 30 to 40 % due to significant loss via leaching, volatilization and drift. The excessive use of chemical fertilizers leads to soil contamination and poses environmental hazards, hence this has led to scientists to explore eco-friendly alternatives. Nanotechnology has emerged as a promising option (2).

Nanotechnology is a rapidly advancing field that involves manipulating materials at the nanoscale, offering innovative solutions in various industries, including agriculture. Materials with dimensions smaller than 100 nm are classified as nanoparticles (3). Nanofertilizers are usually 30 to 40 nm in size and are far more efficient in nutrient delivery (50-70 %) than conventional fertilizers (4). They enable controlled nutrient release thereby improving soil health and plant growth while reducing environmental impact (5). By encapsulating essential nutrients, they ensure a gradual release, enhancing plant uptake and minimizing nutrient loss. Their nanoscale properties also improve absorption and bioavailability of nutrients leading to increased crop biomass production (6). Nanofertilizers offer a promising, sustainable alternative to traditional fertilizers, supporting efficient and eco-friendly agricultural practices due to their unique physicochemical characteristics. Previous research studies have explored specific aspects of nanofertilizers on physical and chemical properties of soil on individual crops but studies lack an integrated approach. Challenges such as nutrient runoff, environmental sustainability and economic feasibility, remain inadequately addressed. Furthermore, uncertainties about biocompatibility and the long-term environmental effects of nanofertilizers also need to be evaluated. However, Nanofertilizers have several drawbacks that limit their widespread use in agriculture. Their high production costs make them expensive and less accessible for farmers. Additionally, the long-term environmental and health risks associated with the accumulation of nanoparticles in soil, water and food chains remain uncertain. The lack of standardized regulations and safety guidelines further raises concerns about their proper application. Some nanoparticles may also be toxic, potentially harming soil microbes and beneficial organisms, which could disrupt soil health (7). This review addresses these gaps and provides knowledge on topics such as application of nanofertilizers in boosting crop productivity, controlling nutrient release and enhancing nutrient uptake. It also seeks to address key concerns related to their environmental impact and economic scalability by examining case studies and experimental findings. This review aims to support the sustainable farming practices and encourage the responsible integration of nanofertilizer into agriculture and emphasizes need for further research.

Origin of Nanofertilizers

The contemporary era of nanotechnology signifies notable advancements in the manipulation and utilization of materials at the nanoscale (1 to 100 nm). This era started with decades of scientific research and technological development, with a focus on harnessing the unique properties of nanomaterials for a wide range of applications across various fields (8) (Fig. 1).

Nanotechnology was explored as a field of scientific utility and technological advancement in the late 20th century. Interest in and development of nanofertilizers and their application in agriculture, began to grow in the early 2000s. Early in the new millennium, researchers began to explore the potential uses of nanotechnology in agriculture, specifically exploring the field of nanofertilizers. Initial studies were focused on comprehending the dynamics of nanoparticles within soil matrices and their interplay with plant organisms (9). At the same time, scientists started looking into using nanomaterials like metal and metal oxide nanoparticles as a means of promoting the delivery and transportation of nutrients.

From the year 2010, a surge in interest for use of nanoparticles in agriculture was noted and progress was made towards development of nanofertilizers with an aim to support sustainable agriculture and better nutrient management. Studies demonstrated that use of nanofertilizers increased uptake of nutrients which resulted in higher crop yields. Scientists explored a wide range of nanomaterials and developed different compositions to improve controlled release, targeted delivery and nutrient distribution (9). Beyond the transportation of nutrients, the scope of nanotechnology

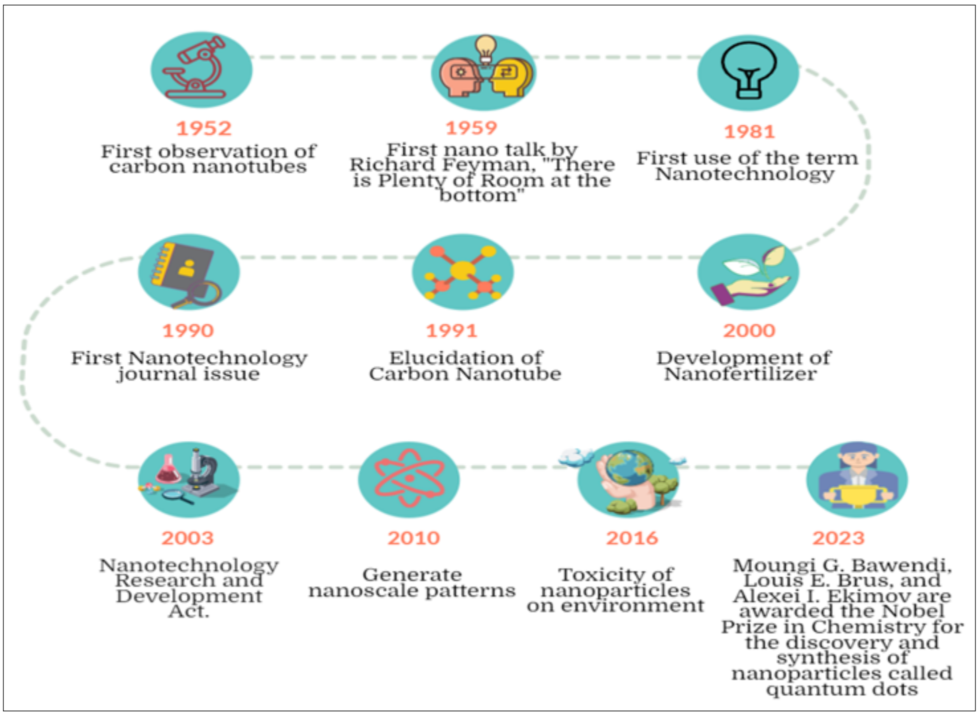

Fig. 1. Overview of the history of development of nanotechnology.

was expanded for use in disease prevention, stress tolerance and the improvement of plant growth properties through nanotechnology. The scientific research on nanotechnology is still in its early stages, the fundamental ideas behind it have been developed over a longer period of time (10).

Synthesis of Nanofertilizers

Physical (top-down) and chemical (bottom-up) approaches are employed in the synthesis of nanofertilizers to deliver essential plant nutrients (Fig. 2).

Top-down approach

Using the top-down method, a large material is divided into nanosized entities. This process requires particular pressure and temperature conditions, is well-known for its complexity, high cost and substantial energy consumption. The imperfect surface structure of the nanoparticles synthesized is a major problem with the top-down approach (11). Techniques like laser ablation, etching, sputtering, electro-explosion and mechanical milling are a part of a top-down approach.

Bottom-up approach

The bottom-up approach is more cost-effective, but it releases toxic material in the processing. Materials are synthesized via atom by atom, molecule by molecule, or cluster by cluster in this approach. A lot of these methods are still in the research and development stages. Only few methods are recently being applied to the commercial manufacturing of nanopowders (12). This technique includes chemical vapour deposition, solvothermal and hydrothermal methods, sol-gel methods, soft and hard templating methods and reverse micelle methods.

Types of Nanofertilizers

The materials used in the production of nanofertilizers can be categorized according to their composition (Fig. 3).

Action-based nanofertilizer

These fertilizers are good for sustainable agriculture because they provide several advantages, including better nutrient utilization, controlled nutrient release, targeted nutrient delivery, increased plant growth and decreased nutrient loss (13).

Controlled release nanofertilizer/Slow release nanofertilizer : Slow-release nanofertilizers (SRNFs) primarily consist of nanocomposite-based fertilizers. Use of controlled-release nanofertilizers have become a viable option to overcome the problems like nutrient leaching and inefficient nutrient arising from conventional fertilizers. The nutrient release pattern and speed are determined by the quality of the coatings. The majority of CRNF is composed of coated material that contains the water-soluble nutrient source. Both inorganic and organic materials can be utilized as the coating and matrix to create CRNF. Inorganic materials include phosphogypsum, bentonite, sulphur, etc. Organic polymers include synthetic materials such as polyethylene, polyurethane, alkyd resin, etc, or natural materials such as chitosan, starch, cellulose, etc (14). One of these advantages of using these fertilizers is increased nutrient use efficiency since the regulated release of nutrients permits continuous

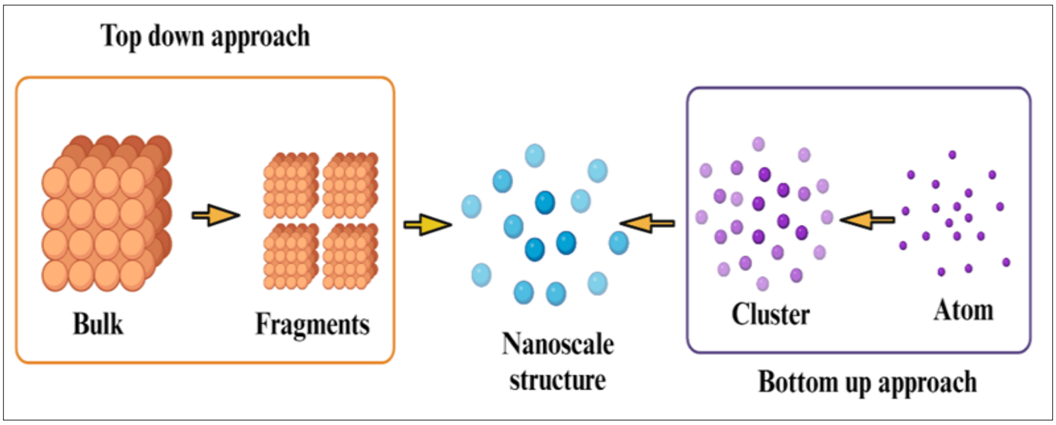

Fig. 2. Approaches followed during synthesis of nanoparticles.

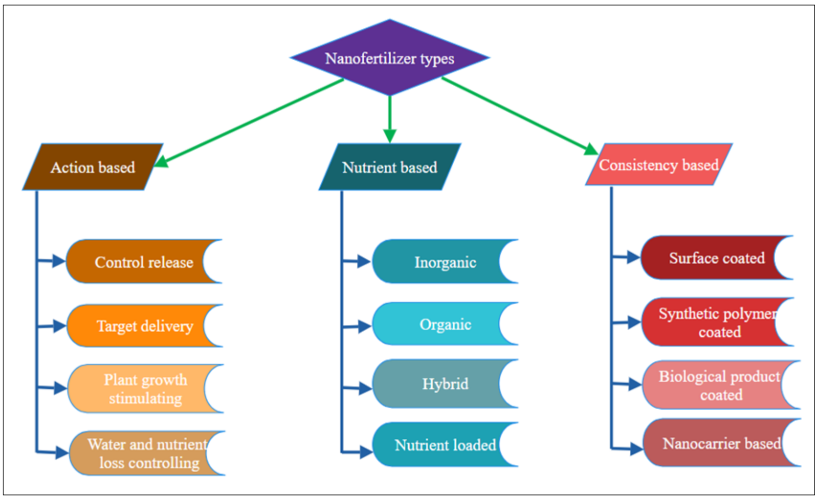

Fig. 3. Types of nanofertilizers.

delivery, which enhances plant nutrient uptake and lowers fertilizer application rates (15). Additionally, these fertilizers do not exert any toxic effect on environment. The effect of various control release nanofertilizers on crops are given in Table 1. Various types of control release nanofertilizers are given in Fig. 4.

Carbon-based nanofertilizer : Carbon is indispensable for sustaining life, as it constitutes the backbone of all organic compounds and participates in crucial biochemical process. Carbon nanomaterials (CNMs) demonstrate great potential as carriers for fertilizers due to their stable molecular structure, even distribution and minimal toxicity. Varieties of carbon-based nanomaterials encompass fullerenes, carbon nanotubes, graphene and its derivatives, graphene oxide, nanodiamonds and carbon-based quantum dots (16). Fullerenes are synthesized using techniques such as arc discharge or chemical vapour deposition, while carbon nanotubes (CNTs) are produced through pyrolysis or catalytic decomposition. Graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO), are obtained by chemically or electrochemically exfoliating graphite. Nanodiamonds are created via high-pressure, high-temperature (HPHT) processes or detonation synthesis. Carbon quantum dots (CQDs), on the other hand, are synthesized using methods like pyrolysis or laser ablation (17). Saxena et al. (18) investigated different concentrations of water-soluble carbon nanoparticles (ws-CNPs) derived from naturally occurring raw CNPs found in biochar. They applied ws-CNPs at concentrations ranging from 10 to 150 mg/L in soil for 20 days. The findings revealed stimulation in growth after a treatment of 50 mg/L resulting in increase in root and shoot lengths by threefold as compared to controls. Additionally, Wang et al. (19) reported that exposure of graphene oxide (GO) at a concentration of 0.1 g/L to the soil, which increased the activity of anaerobic ammonium-oxidizing bacteria by 10 %.

Chitosan-based nanofertilizers : Chitosan-based nanofertilizers (CBNFs), produced from the biopolymer chitosan through chitin deacetylation, hold great promise for sustainable agriculture due to their eco-friendly and biodegradable nature (6). These fertilizers are created using methods like ionic gelation, spray-drying, emulsion-diffusion and nanoprecipitation, which allow for effective nutrient delivery and controlled release. The properties such as antimicrobial activity, chelating capacity and environmental compatibility of chitosan make them act as an excellent medium for nutrient transport (20). Potassium-incorporated chitosan NPs (CNK) and chitosan NPs (CN) are slow-release nanofertilizers that are used to counteract soil nutrient losses and prevent land degradation caused by conventional fertilizers. Kumaraswamy et al. (21) reported that a foliar spray of 0.08 %

Table 1. Effect of various nanofertilizer on crops

Nanofertilizer type	Nanomaterial used	Crop species	Response	Reference
Carbon-based nanofertilizer	Multiwalled carbon nanotubes	*Zea mays*	Enhance plant growth by regulating the essential enzymes engaged in carbon and nitrogen metabolism, thereby enhancing carbohydrate synthesis and nitrogen utilization efficiency, resulting in improved overall plant growth	(38)
Chitosan-based nanofertilizers	Chitosan NPK fertilizer	*Triticum aestivum*	Increases in harvest index, crop index and mobilization index of wheat	(39)
Clay-based fertilizer	manganese nanoclay polymer composites	*Triticum aestivum*	Boosted soil enzymatic activities, specifically dehydrogenase and acid–alkaline phosphatase activities, leading to enhanced wheat grain yield	(40)
Nanocapsule-based nanofertilizer	Nanocapsule - potassium	*Capsicum frutescens*	Reduces the amounts of antioxidant enzymes, maintains the relative water content, protects antioxidant activity and lowers malondialdehyde levels to lessen the negative effects of high temperatures	(41)
Nanogel-based	Calcium Phosphate nanogel	*Abelmoschus esculentus*	Enhanced germination rate, improving activity of enzymes and increased fruit weight	(42)
Zeolite-based nanofertilizers	Nanozeolite urea	*Zea mays*	Consistently observed increases in growth, yield, quality and nutrient uptake	(43)

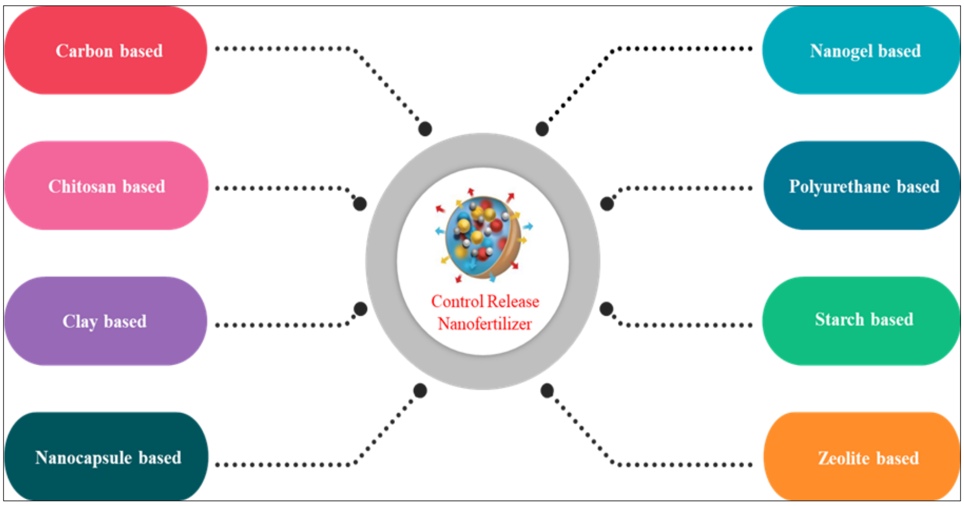

Fig. 4. Types of control release nanofertilizer.

chitosan silicon nanofertilizer (CS-Si NF) improved the yield of maize by 43.4 %. The CS-Si NF could be attributed to the slow release of Si from NF. The incorporation of NPK fertilizer sources, such as urea, calcium phosphate and potassium chloride, into chitosan with methacrylic acid (MAA) nanoparticles enabled the controlled release of nitrogen, phosphorus and potassium nutrients (22).

Clay-based nanofertilizers : Since clay-based NPs have large surface areas and nanolayer reactivity, they can be utilized to create CRF formulations. Nanoclay is crucial to the synthesis of CRF because of the active surface it provides for several physicochemical and biological processes. These nanofertilizers are typically synthesized using techniques like exfoliation, intercalation and surface modification of clay minerals such as montmorillonite, kaolinite and bentonite (23). The modified clay nanoparticles can encapsulate or adsorb nutrients, allowing controlled release of nutrients and reduce nutrient leaching. According to Verma et al. (24), nanoclay-polymer composite, made from modified cetyltrimethylammonium bromide (CTAB) treated nanoclay, showed better nutrient retention, nutrient uptake and optimal release rates to wheat plants, especially in P deficient soil. Rakshitha et al. (25) showed that nitrogen losses can be reduced when urea and urea ammonium nitrate (UAN) are loaded into nanoclay polymer composites (NCPCs) which act as slow-release N fertilizers. The results revealed that UAN loaded NCPC effectively improved nutrient uptake (51 %), agronomic use efficiency (64.2 %) and apparent nitrogen recovery (92 %) in rice.

Nanocapsule-based nanofertilizer : Nanocapsule-based nanofertilizers are innovative nutrient delivery systems that encapsulate nutrients within nanostructured shells, enabling precise and controlled release. These nanocapsules are commonly produced using techniques like polymerization, interfacial deposition, or self-assembly, utilizing biocompatible materials such as chitosan, alginate, or synthetic polymers (26). Petosa et al. (27) consist of capsules having silica, metal oxides, lipids, biopolymers and carbon nanotubes. This technology reduces nutrient losses due to leaching or volatilization and enhances plant nutrient uptake. Additionally, the gradual nutrient release minimizes the risk of leaching. Exposure of wheat to Mesoporous silica nanoparticles (MSN NPs) ranging from 500 to 1000 mg L^{-1} resulted in enhancement in plant biomass, total protein levels, chlorophyll content, seed germination rates and photosynthetic activity. Remarkably, even exposure to high concentrations (2000 mg L^{-1}) also did not induced any negative effects such as oxidative stress in plants (28).

Nanogel-based nanofertilizer : Nanogel-based nanofertilizers employ hydrogel-based nanostructures for efficient and controlled nutrient delivery, offering significant potential for sustainable agriculture. These nanogels are produced through techniques such as polymerization, cross-linking, or self-assembly, using biopolymers like chitosan and alginate or synthetic materials such as polyacrylamide (29). The elements nitrogen, phosphorus and potassium, essential for promoting plant growth, are impregnated into the nanogels (30). Chitosan-based nanogels have demonstrated a 40 % increase in nutrient uptake and significantly improved maize growth compared to traditional fertilizers. According to Lee et al. (31), lignin is a cheap, biodegradable resource that can be used as nanogel extensively without negatively impacting the environment. However, issues of production scalability and cost-effectiveness need to be addressed for broader adoption.

Polyurethane-based nanofertilizers : A new class of fertilizers known as polyurethane nanofertilizers which are made of organic units joined by urethane linkages. These fertilizers are manufactured through techniques such as interfacial polymerization, emulsion polymerization, or solvent evaporation, enabling the encapsulation of key nutrients like nitrogen, phosphorus and potassium within polyurethane nanostructures (32). The properties like high mechanical strength, chemical stability and tunability, polyurethane facilitates the gradual release of nutrients, thereby minimizing losses from leaching or volatilization. The process of ring-opening metathesis polymerization (ROMP), which entails generating a monomer from two distinct molecules with a double bond before polymerizing it, is commonly used to create polyurethane-based nanofertilizers (33). Cotton seed oil can be used to produce polymeric materials because of they are easily available, affordable, renewable and biodegradable resources. Since polyurethane is superhydrophobic, it keeps away water from coming into contact with the fertilizer when it's liquid, increasing surface roughness and lowering surface energy (34).

Starch-based nanofertilizer : Starch is an effective nutritional carrier. It is synthesized via methods such as nanoprecipitation, emulsion cross-linking, or enzymatic hydrolysis, resulting in nanostructures capable of encapsulating essential nutrients. The slow-release property of starch-based fertilizers can be achieved by physically restricting nutrient release through adsorption and encapsulation within the starch matrix. Starch-based nanofertilizers include starch-based nanocrystals that get easily dissolved in water or can be sprayed onto plants in liquid form. According to the findings, plants treated with this nanofertilizer exhibited notably greater height compared to those in the control. Additionally, the nanofertilizer displayed efficacy in neutralizing reactive oxygen species (35).

Zeolite-based nanofertilizer : Nanozeolites can release nutrients to the plantsat a slow rate, which increases the availability of nutrients in crops and prevents the loss of nutrients from denitrification, volatilization and leaching. The synthesis of nanozeolites involves several interconnected parameters that influence their formation and properties. These include use of a structure that is directing agents or organic additives, the choice of precursors and synthesis suspensions, and the initial sources of silicon and aluminum. Additionally, conditions such as temperature, pressure and time, along with heating methods like sonication, microwave, or conventional heating play a crucial role during synthesis. Nanozeolites with particle sizes in the range of 1-1000 nm and well-defined pore structures, which are categorized into micropores (<2 nm), mesopores (2-50 nm) and macropores (>50 nm) (36) are synthesized. A study demonstrated that nitrogen was applied in the form of zeolite bases No_3- (6.2 % N) and zeolite-based NH_4+-N (12.6 % N). The slow and steady release of N nanozeolite loaded assisted in the reduction of nitrous oxide emission (1.8 mg m^{-2} day^{-1}) in fertilized soils in comparison to conventional fertilizer (2.7 mg m^{-2} day^{-1}) applied soils. There was a slight reduction in methane emission (34.8 mg m^{-2} day^{-1}) from the nanofertilizer applied soils than control (36.8 mg m^{-2} day^{-1}) (37).

Nanofertilizers for targeted delivery : Target-based nanofertilizer carriers comprise carbon-based nano-emulsions, nano-hydroxyapatite, nano-coated urea, nano-iron oxide NPs, nano-hydroxyapatite and nano-encapsulated micronutrients (44). These innovative formulations lead to increased agricultural productivity and reduced environmental impact by facilitating the controlled release and enhanced absorption of nutrients. Bhavani (45) studied the urea-coated hydroxyapatite (UHA) nanoparticles and concluded that UHA (36 % N) enhanced the NUE by reducing nitrogen losses than conventional urea application in rice.

Water and nutrient loss controlling fertilizers : This technique involves enclosing the nanofertilizer within a porous matrix, allowing for gradual nutrient release (7). In another strategy the surface of the nanofertilizer is modified to enhance its water-holding capacity and reduce evaporation losses by making it hydrophilic (46). Nanofertilizers designed to regulate water and nutrient loss in soil include urea coated with nanoparticles of various elements such as iron oxide, sulfur, calcium, magnesium, zinc, copper, molybdenum, boron, ammonium sulfate and potassium (47). Mali et al. (48) have suggested nanobeads and nanoemulsions as two popular nanofertilizers that effectively manage soil water and nutrient loss.

Nutrient-based nanofertilizer

Nutrient-based nanofertilizers are materials that contain essential macro- and micronutrients, such as nitrogen, phosphorus, potassium, iron and manganese at the nanoscale and are intended to be delivered to the plant rhizosphere under controlled circumstances. Through the encapsulation or coating of nutrients, they enable a controlled release of nutrients and reduce leaching and losses via volatilization (49). The nanofertilizers with increased surface area to volume ratio increase the efficiency of nutrient usage, promoting plant growth and yield. Application via foliar sprays, soil incorporation, or nanoemulsions helps in accurate nutrient delivery, leading to increase in crop yields and lowering of soil toxicity (26).

Inorganic-based nanofertilizer : Essential nutrients like nitrogen, phosphorus and potassium can be supplied to plants by inorganic nanofertilizers, which comprise metals, metalloids and non-metallic nanoparticles. These fertilizers can be utilized to increase agricultural yields by increasing the efficiency of plants for nutrient absorption (50). Inorganic nanofertilizers are categorized into two types: macronutrient-based and micronutrient-based nanofertilizers. Effect of inorganic nanofertilizer in different crops has been given in Table 2.

Macronutrient nanofertilizer:

Nitrogen nanofertilizer : These nanofertilizers are synthesized using techniques such as nanoprecipitation, encapsulation, or coating nitrogen sources like urea with nanomaterials such as silica, chitosan, metal oxides, graphene and carbon nanotubes (26). The gradual release of nitrogen facilitated by this particle combination increases the nitrogen content and enhances the nutrient absorption accessible to plants in the soil. Porous nanomaterials like zeolites coated nanourea play a crucial role in minimizing nitrogen (N) loss by

Table 2. Effect of inorganic nanofertilizer response in different crops

Nanofertilizer type	Concentration	Crop species	Response	Reference
Nitrogen	25-100 % n-NF	*Oryza sativa*	Nano-N fertilizer enhances plant height, dry matter yield and the number of tillers in rice. It helps to minimize nitrogen runoff and leaching, promoting nitrogen utilization by plants	(75)
Phosphorus	nano-P @ 494.21 mL ha^{-1}	*Triticum aestivum*	Increase more effective for achieving higher growth, yield, yield attributing properties and nutrient uptake of plants	(76)
Potassium	1.06 g MOP in 0.88 L of nanopolymer	*Zea mays*	Usage of nanofertilizer at a reduced rate of 2.5 times compared to the RDF resulted in a notable enhancement of growth parameters, yield and quality attributes, nutrient content and uptake by the plants of maize crops	(77)
Calcium	20 % NCaP soil application in combination with a 5 % NCaP foliar application	*Phaseolus vulgaris*	Nano CaP has enhanced plant growth, nutrient content in shoot and root and improved yield. Has the ability to penetrate deeply into both roots and leaves, thereby enhancing the physiological traits and ultimately improved the yield of snap bean plants	(78)
Magnesium	50 mg/L dose of Mg nanofertilizer	Green beans	Nano-Mg sulfate enhanced the accumulation of bioactive compounds and antioxidant capacity, thereby improving the nutritional and nutraceutical quality when compared to high doses of traditional Mg sulfate (300 mg/L)	(79)
Sulphur	50 kg ha^{-1} NS-BOP Nano sulphur bio-organic phosphate	*Zea mays*	NS-BOP led to decrease in soil pH while concurrently enhancing the availability of nutrients i.e., N, P, K and S. And improved agronomic characteristics aimed at enhancing crop growth and nutrient availability in the soil	(80)
Boron	10 mg dm^{-3}	Faba bean	Enhance nitrogen, phosphorus, boron chlorophyll content in faba bean leaves, along with higher dry matter content	(81)
Copper	50 mg/kg for soil application and 40 ppm for foliar application	*Vigna unguiculata*	In both soil and foliar applications, increment in morphological attributes, enhancement in antioxidant concentration and chlorophyll contents	(82)
Iron	50 mg kg^{-1}	*Solanum lycopersicum*	Organically coated Fe_3O_4 nanoparticles, particularly Fe_3O_4@HA, improved bioavailability, leading to an enhanced total iron uptake in the shoot. It is an effective, cost-efficient and biocompatible solution for addressing iron deficiency in soil	(83)
Zinc	80 mg kg^{-1} and 20 ppm	*Zea mays*	Improved plant growth, photosynthetic pigments and antioxidant activity	(73)

facilitating a demand-driven release of nitrogen and by enhancing plant nitrogen uptake, as demonstrated by Abdel-Aziz (39). Application of 100 % recommended dose of N (150 kg ha^{-1}) through urea + two foliar sprays of nanourea @ 4 mL L^{-1} of water improved the plant growth, nutrient uptake and profitability of hybrid rice cultivation (51).

Phosphorus nanofertilizer : Phosphorus - based nanofertilizers are designed to overcome the challenges of low bioavailability and inefficient phosphorus utilization of conventional fertilizers by plants. They are produced using techniques like sol-gel methods, hydrothermal processes, or encapsulation, integrating phosphorus sources such as phosphates into nanocarriers like silica, chitosan, or zeolites. Their nanoscale design enables a controlled and targeted release of phosphorus, enhancing plant uptake while reducing losses due to runoff and soil fixation. Substituting traditional bulk annual applications, slow-release phosphorus nanofertilizer (Pnf) was applied throughout the crop cycle (52). The utilization of nanozeolite phosphorus (with 20.9 % P_2O_5) is crucial for promoting crop growth, increasing peanut oil content and mitigating pollution risks by improving nutrient utilization efficiency (53). Kalmi growth, uptake and concentration of phosphorus (P) improved after application of nanophosphorus in comparison to the conventional bulk phosphorus application.

Potassium nanofertilizer : Nanopotassium, another name for potassium nanofertilizers is a contemporary development in agriculture (54). Nanopotassium are typically synthesized using methods *viz.*, encapsulation, ion-exchange, or nanoprecipitation, where potassium sources such as potassium chloride or potassium sulfate are integrated into nanomaterials. These fertilizers are made up of tiny particles, and they can reach plant roots by penetrating the soil more deeply. Besides promoting root and shoot growth, nanopotassium improved the absorption of other nutrients like nitrogen, calcium, magnesium and phosphorus. It usually works better in the root region (55). Rostami and Amiri (56) showed that application of 3 kg ha^{-1} of potassium nanofertilizer increased the photosynthetic rate in soybean. Its growth, yield, quality and WUE increased under irrigation deprived conditions.

Calcium nanofertilizer : Various types of calcium-based nanofertilizers have been developed, including those derived from calcium carbonate and others formulated from calcium nitrate combined with calcium phosphate. These nanofertilizers have demonstrated efficacy in enhancing crop growth and yields (57). The study showed that CaO nanoparticles can used as a foliar nanofertilizer for various fruits like cherries, apples, peaches, etc. This method offers an eco-friendly alternative to traditional fertilizers due to its high availability, low material consumption, easy preparation and cost-effectiveness. The increase in Ca^{2+} content in the peel and cell width indicates efficient utilization of the nanoparticles by plants, converting them into a more accessible source of calcium and reducing their accumulation in the fruit (58).

Magnesium nanofertilizer : Magnesium - based nanofertilizers are made of magnesium sulfate or magnesium oxide. Liao et al. (59) reported that crop growth and yield can be effectively increased with the use of magnesium-based nanofertilizers. Application of 60 ppm MgO nanoparticles through foliar application resulted in enhanced growth and yield when compared to conventional $MgSO_4$ in cotton. Furthermore, treatment of MgO nanoparticles improved fiber quality parameters such as fibre length and strength in cotton more effectively than sulfate-based Mg fertilizers (60). Green-synthesized MgO nanoparticles reduced arsenic accumulation by 62 % in rice shoots, enhancing growth and restoring primary metabolites. Improvement in antioxidant defense also improved potential for sustainable rice production in metal-contaminated soils (61).

Sulfur nanofertilizers : Numerous sulfur-based nanofertilizers have been developed, comprising diverse compositions. Some are made from elemental sulfur, while others are formulated from sulfur compounds like sulfur-coated urea or sulfur-coated potassium sulfate (62). Thirunavukkarasu et al. (63) stated that the utilization of nano-S at a rate of 30 kg S ha^{-1} improved sulfur utilization efficiency. This resulted in a decreased need for sulphur fertilization by 25 % simultaneously increasing soil sulphur reserves without causing any harm to the soil environment.

Micronutrient nanofertilizer : Small amounts of micronutrient elements like boron, iron, manganese, zinc, chlorine and copper affect the plant physiology. Nanoparticles particularly used as micronutrient nanofertilizers have a notable effect as agricultural input that is capable of providing plants with essential micronutrients more efficiently than conventional fertilizers. Plants treated with these nano formulations exhibit enhanced resilience to both biotic and abiotic stresses, leading to increased yield and improved nutrient uptake.

Boron nanofertilizer : Nanoparticles are generated through the combining of borate with various substances, such as humic acid to develop boron-based nanofertilizers. These nanoparticles can be directly applied to crops or soil as a foliar spray. These methods allows boron-based nanofertilizers to penetrate plant cells and provide them with micronutrients (64). Notably, foliar application of nano boron at a concentration of 3 mL L^{-1} increased plant growth and leaf chlorophyll content in wheat (65).

Copper nanofertilizers : Copper nanofertilizers demonstrate remarkable efficacy in nutrient delivery to plants, as minute Cu particles can permeate into plant cells and supply essential nutrients to the root system. The quick and effective absorption of nutrients is protected by this direct delivery technique. Copper nanofertilizers can be applied easily and effectively. These nanofertilizers provide a reasonably priced substitute for conventional fertilizers (66). Application of nano copper fertilizer at a concentration of 1.5 g L^{-1} led to increased branch numbers and leaf area, thus supporting the vegetative growth in broad bean plants (67).

Iron nanofertilizers : Iron nanofertilizers are available in various formulations, such as nanosized iron particles, nano-encapsulated iron and nanocomposites. They intend to enhance the availability of iron for plants (68). Liu et al. (69) developed nano-encapsulated iron, that include particles coated with a protective barrier, such as lipids or biopolymers, to prevent oxidation and prolong the presence of iron in the soil. Iron particles combined with other substances like zeolite or clay are known as nanocomposites which enhanced Fe availability providing an adsorptive surface. Treatment of seeds with iron oxide (Fe_3O_4) NP increased levels of ascorbate peroxidase but decreased malondialdehyde (MDA) content in both the roots and leaves of wheat (70).

Zinc nanofertilizer : Applying ZnO nanofertilizers in the soil increases the availability of zinc to plants, which in turn enhances crop yields. Sheoran et al. (71) reported that use of ZnO nanofertilizers can reduce the zinc content that leaches from the soil, reducing the possibility of environmental contamination. Foliar application of ZnO NPs in wheat (*Triticum aestivum*) significantly improved growth, yield, biochemical traits and structural parameters, increasing chlorophyll, protein and antioxidant enzymes, while enhancing stem and root development (72). Azam et al. (73) found that ZnO nanofertilizers increased maize growth by 61.1 % and synthesis of photosynthetic pigments by 51.8 % through soil application, while foliar treatments boosted growth by 59.28 %, enhancing yield in Zn-deficient soils. Tarafdar et al. (74) explored the biosynthesis of zinc nanoparticles as eco-friendly nanofertilizers for pearl millet. Nanoparticles (15-25 nm) improved the shoot length, root area, enzyme activities including phytase and grain yield.

Organic-based nanofertilizer : Organic nanofertilizers are derived from natural sources. They are environmentally friendly and can modify pH levels and retain soil moisture, aiding plants in more effective absorption of essential nutrients (84). Natural polymers i.e., gum, xanthan gum, guaran, phytagel, gum gopal, Indian tragacanth gum, tamarind seed polysaccharide, touch me not plant seed mucilage and modified clays can be used to create organic nanofertilizers (85). Furthermore, addition of organic nanofertilizers can greatly enhance soil structure by increasing porosity and aggregation, which in turn improves aeration, root and water infiltration (86).

Hybrid-based nanofertilizer : Hybrid-based nanofertilizers are synthesized through methods like sol-gel processes, co-precipitation, or polymer-assisted encapsulation, integrating nutrients with nanocarriers such as carbon-based materials, zeolites, or silica nanoparticles. The main advantages of using these nanofertilizers are enhanced nutrient stability, controlled release and increased bioavailability, leading to improved plant uptake efficiency. According to Tarafder et al. (87), hybrid nanofertilizers are a combination of traditional and nano-based fertilizers used to improve nutrient accessibility and enable a slow and continuous release of nutrients. These nanofertilizers enhance the fertilizer efficiency while minimizing the environmental footprint of fertilizer production and application (88). Additionally, they may reduce the overall fertilizer requirement for plants, potentially leading to cost savings for farmers (89).

Consistency-based nanofertilizers

Consistency-based nanofertilizers, including surface-coated and nanocarrier-based types, offer sustainable agricultural solutions enhanced nutrient utilization and minimizing environmental impact (44).

Surface-coated nanofertilizers : These fertilizers are made from silica, iron and other nutrient-rich nanoparticles, adhere to plant surfaces and penetrate cells, enhancing nitrogen efficiency and phosphorus absorption. These are produced by applying biological polymers like chitosan or synthetic materials such as polyethylene glycol (PEG) through methods like in-situ polymerization or electrostatic deposition, effectively reducing nutrient loss and enhancing availability (90, 91).

Nanocarrier-based fertilizers : These nanofertilizers are based on mesoporous silica nanoparticles (MSNs) created using sol-gel or hydrothermal techniques, which enable efficient nutrient encapsulation, controlled release and greater stability (92). Mesoporous silica nanoparticles (MSNs), synthesized through sol-gel or hydrothermal methods, enable controlled nutrient release, reducing leaching and enhancing efficiency. Urea-loaded MSNs support maize growth and drought tolerance by gradually supplying nitrogen. Hydroxyapatite (HA) nanoparticles, made of calcium phosphate, bind urea for slow nitrogen release, minimizing losses and improving crop productivity (93). Chitosan-based nanocarriers, derived from natural polymers, enhance nutrient retention, promoting better uptake while preventing over-fertilization. Layered double hydroxide (LDH) clays act as carriers for nitrogen and phosphorus, ensuring controlled release through ion exchange. These nanocarriers improve soil health, boost nutrient efficiency and reduce environmental runoff. Their application contributes to sustainable agriculture by optimizing fertilizer use and minimizing nutrient waste. However, challenges such as optimizing coating techniques, reducing production costs and addressing potential environmental effects need to be addressed.

Benefits of nanofertilizers

Enhanced nutrient efficiency and uptake mechanisms

With a large surface area and particle size smaller than the pores, the nanofertilizer can penetrate in a plant's root system and leaves, more deeply and enhance their uptake and nutrient-use efficiency. Improving the NUE is an essential defensive tactic against the loss of nitrogen in the soil due to denitrification, volatilization, leaching and fixation, especially when it comes to nitrate (NO_3^-) and nitrite (NO_2^-) forms (94). A study showed that the application of zinc oxide nanoparticles significantly improved zinc uptake, shoot dry weight and root length in wheat plants compared to traditional ZnS (95). Similarly, in another study, the application of FeO NPs at a dosage of 500 mg L^{-1} NP resulted in increased chlorophyll content and uptake of iron in wheat plants, ultimately leading to improved yield and increased (NUE) by 27 % (70). Studies have indicated that traditional fertilizers particularly nitrogen-based fertilizers show a NUE (nutrient use efficiency) of around 30-40 %, phosphorus-based fertilizers have a NUE of 18-20 % and potassium-based fertilizers have an NUE of 60-65 % (96). Nanofertilizers show higher NUE ranging from 58-51 %, while single superphosphate (SSP) and diammonium phosphate (DAP) have lower NUE of 15-16 % (76).

Nanoparticles undergo a sequence of biological and geochemical changes in soil. The nanoparticles interact in soil with plant root exudates and then enters through an epidermal cell wall (97). It was reported that the mucilage secreted by *Arabidopsis thaliana* roots creates a complex of pectin hydrogel around the roots, facilitating the penetration of NP-dye complexes. In foliar spray, the nanoparticles penetrate through leaves in 48-72 hr (98). Stomata serve as entry points for NPs, which then traverse the plant's vascular system via apoplastic and symplastic routes. Nanoparticles smaller than 20 nm are generally optimal for foliar absorption (99). Wang et al. (19) found TiO_2, Mg and Zn nanoparticles (NPs) concentration in leaves (1.87 %, 8.13 % and 5.74 %) is more than in roots (5.45 %, 21.2 % and 13.9 %), respectively. Small NPs (TiO_2 - 27 nm, MgO - 35 nm, ZnO - 45 nm) pass through stomata easily, while larger ones hindered stomatal function, affecting transpiration and photosynthesis (Fig. 5).

Improved soil health and microbial interactions

The soil erosion problems can be resolved and general soil health can be strengthened by using nanofertilizers. This is because nanofertilizers improve soil structure and enhance moisture retention. Rajput et al. (100) investigated the possible dangers of supplementing high concentrations of nanoparticles in soil and their impact on microbial beneficial communities, crops and soil characteristics. The behavior of nanomaterials and their interactions with microorganisms and plants are largely determined by the properties of the soil, apart from particle size.

Dimkpa (101) stated that several factors are known to have an impact on the chemical properties of nanoparticles, including soil pH, ionic strength, organic matter content and phosphate concentration. Reactive oxygen species produced as a result of dissolution of the nanofertilizers at lower pH, which can be harmful. The stabilization of nanoparticles by naturally occurring organic matter in soil can change the surface chemistry of the particles, which in turn have a huge impact on microorganisms and plants. Asadishad et al. (102) found that silver (nAg), zinc oxide (nZnO) and copper oxide (nCuO) nanoparticles are toxic to soil microbes at concentrations of 1-100 mg/kg, while titanium dioxide ($nTiO_2$) appears non-toxic within this range. However, at higher doses (500 mg/kg), $nTiO_2$ reduced ammonia-oxidizing archaea and affected nitrification. nZnO and nCuO showed strong toxicity even at lower concentrations, highlighting potential ecological risks of nanoparticle use in agriculture.

Eco-friendly nature

Nanofertilizers offer a promising solution for tackling the environmental effects associated with chemical runoff in agriculture. The nutrient delivery system provided by nanofertilizers is more accurate and regulated than that of traditional fertilizers. Conventional fertilizers frequently cause water contamination by leakage of excess nutrients into surface and groundwater sources (103). Reduced nutrient runoff into surrounding ecosystems results from their microscopic formulations, which assist in better absorption and increase nutrient uptake. Nanofertilizers ensure long-term environmental resilience and well-being by mitigating nutrient runoff, which helps to preserve fragile ecosystems and encourage sustainable agricultural methods. It was observed that employing controlled -release fertilizer (15-9-7) at a dosage of 50 % F led to a 21.6 % reduction in nitrogen runoff and a 24.5 % decrease in leaching loss (69). Furthermore, it resulted in a 9.8 % rise in residual mineral N in the soil and a 5.5 % yield increase in wheat production as compared to conventional fertilizer techniques. Nanofertilizers can help mitigate the negative consequences of fertilizer application, such as runoff-induced soil erosion and contaminated water. It offer a less damaging alternative to the agricultural industry (104).

Economic benefits

Nanofertilizers have the potential to lower the production costs because of their enhanced nutrient utilization efficiency, precise targeting and controlled release mechanisms, which reduce fertilizer losses in agricultural fields. Leon-Silva et al. (105) confirmed that because of their higher absorption rates, lower labour requirements and smaller amounts of fertilizer are required for each application. Nanofertilizers are typically less expensive than conventional fertilizers. They also require fewer applications and a low cost due to their extended soil retention.

There may be significant environmental benefits associated with the lower dosages required for nanofertilizers, but it is unclear whether these benefits outweigh the potential costs (106). However, the adoption of nanotechnology in agriculture could be stimulated by these environmental advantages. Furthermore, use of conventional in combination with nanofertilizers is being widely explored as a means to further increase crop yield (107). By using conventional fertilizers

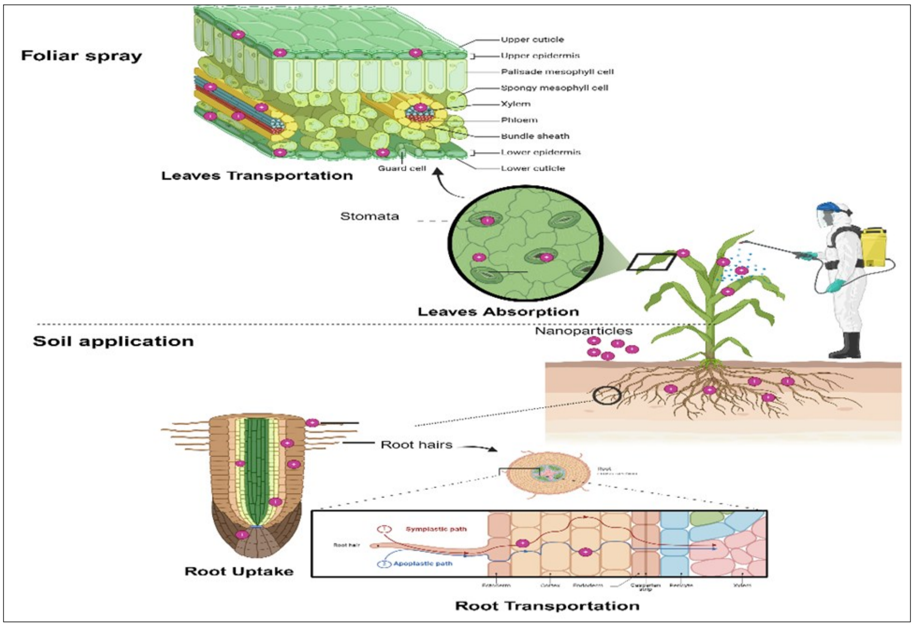

Fig. 5. Uptake mechanism of nanoparticles.

alongside nanofertilizers, farmers can potentially reduce the total cost of fertilizer application while maximizing yield. However, it's crucial to consider that the overall cost of fertilizers is directly influenced by dosage, both for conventional and nanofertilizers. Higher dosages result in a significant cost disparity between the two types of fertilizers. Cai et al. (108) emphasized accurate estimation of revenue changes following the adoption of nanofertilizers. This analysis is crucial for farmers to make informed decisions regarding the implementation of nanofertilizers in their agricultural practices.

Crop-specific impact of nanofertilizers and their responses

Nanofertilizers demonstrate significant crop-specific benefits, promoting growth, yield and biochemical properties. Their targeted use enhances nutrient absorption, enhanced photosynthetic activity and strengthens stress tolerance. The responses depend on crop type, application method and nanomaterial composition, emphasizing their role in sustainable farming. A wide range of nanofertilizers have been used in field to improve crop yields (Table 3).

Advantages of using nanofertilizers over conventional fertilizers

Conventional fertilizers, containing key nutrients like nitrogen (N), phosphorus (P) and potassium (K), are commonly available in forms such as granules, powders, or liquid solutions. They release nutrients immediately upon application, which, if not rapidly absorbed by plants, may lead to nutrient leaching or volatilization (124). Despite their effectiveness, these fertilizers may suffer from limitations in nutrient solubility and uptake efficiency, potentially causing nutrient losses and environmental harm if overused. Excessive nutrient runoff can contaminate groundwater and water bodies, resulting in eutrophication and ecosystem damage. Traditional fertilizers offer cost benefits due to their widespread usage and established manufacturing processes, resulting in lower initial expenses (125).

Nanofertilizers incorporate nanoscale materials, including nanoparticles, nanocarriers, or nanoscale structures, which can be organic or inorganic, depending on the formulation. They enhance the efficiency of nutrient uptake by promoting increased interaction between nutrients and plant roots, facilitated by their small size and expanded surface area, resulting in superior nutrient absorption (126). This contributes to reducing nutrient losses and mitigating environmental impact by optimizing nutrient utilization and controlled release. Previous studies showed that plants can absorb nutrients from nanofertilizers more effectively, reducing waste and guaranteeing optimal nutrient delivery (1). Despite their effectiveness, nanofertilizers often entail higher production costs due to the intricate nature of nanotechnological processes, the requirement for expensive equipment, and strict quality control measures (127). It was reported that the combined application of conventional and nanofertilizers improved crop yields, nutrient uptake, soil mineral N, dehydrogenase activity and soil microbial biomass

Table 3. Effect of crop specific use of nanofertilizer and its response

Crop species	Nanomaterials	Concentration	Mode of application	Response	References
Cereals					
Rice	ZnO	100 ppm	Foliar	Improved the zinc concentration in grain	(109)
Wheat	NCSF +NAA+NK	33.33 mL in 100 L^{-1} water	Foliar	Enhance the grain yield and agronomic productivity	(110)
Maize	SiO_2	10 g kg^{-1}	Soil	Used as a growth promoter it increases the physiological parameter and yield	(111)
Sorghum	Nano urea & DAP	1.5 mL L^{-1}	Foliar	Improved the nutrient content of the grain, nutrient uptake and nutrient use efficiency	(112)
Pearl millet	Nano urea	2 mL of $water^{-1}$	Foliar	Compared to soil application of bulk urea, foliar spray of nano urea increases the grain yield	(113)
Finger millet	Nano urea	0.4 %	Seed and foliar	Combined application of seed treatment and foliar spray enhanced the better growth, yield and generating favorable economic returns	(114)
Pulses					
Pigeon Pea	Nano DAP	4 mL L^{-1}	Foliar	Increase growth attributes and yield parameters	(115)
Chickpea	Nano NPK + Fe + Zn	2 L per plot	Foliar	Nanofertilizers act as a growth promoter and can increase plant growth and seed yield	(116)
Mung bean	Nano boron	90 mg L^{-1}	Foliar	Increase the number of pods and, the number of seeds on the pod	(117)
Black gram	Nano urea	2-4 mL	Foliar	Enhanced the growth parameter and nutrient uptake	(118)
Soybean	Nano P	3 kg ha^{-1}	Foliar	Increased photosynthetic capability has positive effects on its growth, grain yield, grain quality and WUEs, especially under irrigation cut conditions	(56)
Vegetables					
Tomato	Carbon nanotube	10-40 μg mL^{-1}	Seed	Improve seed germination and growth of tomato seedlings	(119)
Okra	Hybrid NF	50 mg	Soil	Increase the nutrient uptake content in soil and water	(87)
Lettuce	nano-hydroxyapatite	200 mg kg^{-1}	Soil	Improved plant growth and P concentration	(120)
Raddish	CeO_2	50 mg kg^{-1}	Soil	Increase fresh biomass and chlorophyll content	(121)
Fruits					
Cucumber	Nano NPK	6 mL	Foliar	Increase plant height and chlorophyll content and record the highest value of firmness and TSS	(122)
Legumes					
Common bean	GA-AgNPs	20 ppm	Foliar	Increased plant height, number of leaves/plants and seed yield	(123)

carbon in wheat-maize and mustard-pearl millet cropping systems (128). But alone, the application of conventional fertilizer diminished the yield when compared to nanofertilizer (Fig. 6).

Nowadays, nanofertilizers have been available commercially. A list of commercially available nanofertilizer products along with the names of their manufacturing companies has been given in Table 4. These products offer an advantage of their use in promoting sustainable agricultural practices.

Challenges and Limitations

While nanofertilizers offer promising benefits, it's essential to acknowledge their limitations and potential drawbacks. Several concerns and detrimental consequences of use of nanofertilizers have been documented (129).

Toxicity concerns and environmental risks

Manjunatha et al. (130) emphasize the importance of conducting comprehensive risk assessments and nano-toxicological evaluations to ensure the safe and responsible use of nanoparticles. The studies suggested that the nanostructure of a substance may pose higher risks compared to its non-nano form/conventional, highlighting the need for careful evaluation. Bayat et al. (131) stressed the necessity of developing scientific approaches to manage the toxicological effects of NP interactions with the environment and biological systems. They emphasize the importance of understanding and mitigating potential risks associated with NP exposure. Rajput et al. (100) constitute the role of the protein corona (PC), i.e., Proteins adsorb onto the surface of nanoparticles to form a biological coating, known as the protein corona. It regulates the interaction between NPs and living systems or cells. They cautioned that incompatible nanoparticle protein corona (NP-PC) interactions can lead to cytotoxic, genotoxic and pathophysiological effects, indicating the importance of understanding these interactions.

NPs have been observed to exhibit phytotoxicity, causing various morphological and physiological effects on plants, including reduced root length, damaged root tips, decreased biomass and chlorophyll degradation. It is noted that cucumber exposed to titanium dioxide (TiO_2) NPs and guar exposed to ZnO-NPs exhibited increased chlorophyll content, while pea exposed to ZnO-NPs and tomato exposed to silver (Ag) NPs showed decreased chlorophyll content, indicating the diverse effects of NPs on plant physiology (132). Application of silver nanoparticles (AgNPs) up to 30 µg mL^{-1} in rice accelerated the root and shoot growth. Beyond the use of AgNPs to 60 µg mL^{-1} leads to the generation of reactive oxygen species (ROS) by NPs can disrupt normal biophysical functions and abiotic stress response mechanisms, leading to oxidative stress and genotoxic effects through the modulation of stress-related genes (133). These findings emphasize the need for careful consideration of the potential risks associated with NP exposure and the development of strategies to mitigate adverse effects.

Ghormade et al. (134) demonstrated that the release of nanoparticles (NPs) into the environment poses significant concerns regarding contamination of soil, water and air. Shoults-Wilson et al. (135) showed that NPs have the potential

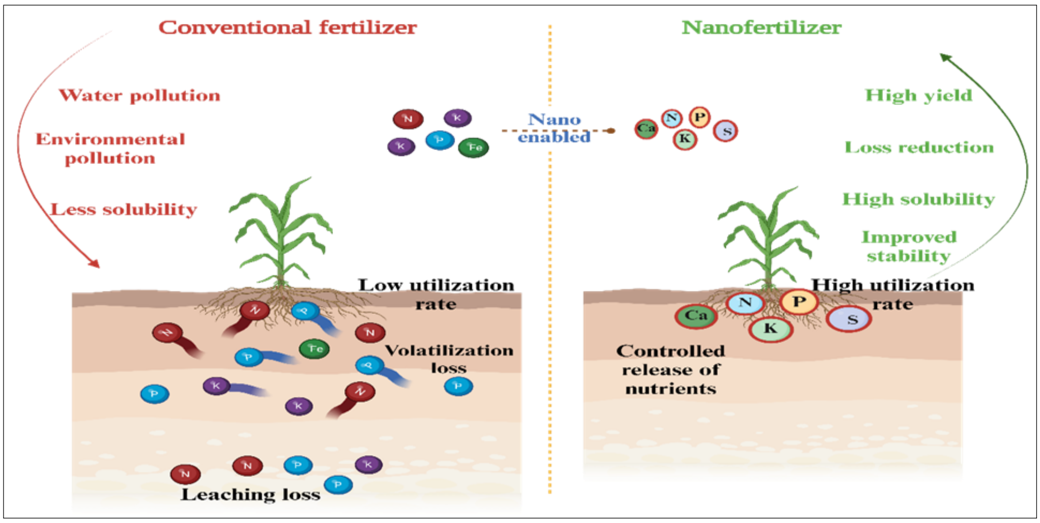

Fig. 6. Comparison of conventional and nanofertilizers.

Table 4. Lists of commercially available nanofertilizer products

Nanofertilizers name	Company name
Nano Urea (500) mL	Indian Fertilizers and Farmers Cooperative Ltd., India
Nano DAP (500) mL	Indian Fertilizers and Farmers Cooperative Ltd., India
Gromor Nano DAP (1000) mL	Coromandel International Ltd., India
TAG NANO (NPK, PhoS, Zinc, Cal) fertilizers	Tropical Agrosystem India (P) Ltd., India
Nano Ultra-Fertilizer (500) g	SMTET Eco-technologies Co., Ltd., Taiwan
Nano Micro Nutrient (EcoStar) (500) g	Shan Maw Myae Trading Co., Ltd., India
Nano Calcium (Magic Green) (1) kg	AC International Network Co., Ltd., Germany
PPC Nano (120) mL	WAI International Development Co., Ltd., Malaysia
Nano Capsule	The Best International Network Co., Ltd., Thailand
Nano Max NPK Fertilizer	JU Agri Sciences Pvt. Ltd., Janakpuri, New Delhi, India
Nano Green	Nano Green Sciences, Inc., India
Hero Super Nano (25) g	World Connet Plus Myanmar Co., Ltd., Thailand
Plant Nutrition Powder (Green Nano) (25) g	Green Organic World Co., Ltd., Thailand
Biozar Nano-Fertilizer	Fanavar Nano-PazhooheshMarkazi Company, Iran

to accumulate in the soil, which may disrupt soil ecosystems and diminish soil fertility. Furthermore, the leaching of NPs from soil into aquatic ecosystems poses risks to aquatic organisms, potentially leading to bioaccumulation and biomagnification within the food chain (136). Owing to these potential risks, further investigation is necessary to understand and mitigate the negative consequences associated with the release of nanoparticles into the environment.

Regulatory hurdles and standardization

The absence of specific regulations governing the use of nano products in many countries has significantly impeded commercialization and hindered progress in future research efforts (137). Gwinn and Tran (138) indicated that the lack of standardization of guidelines within the nanomaterials industry has posed challenges to commercialization. The absence of a consistent definition of nanomaterials and varying restrictions on their usage across nations contribute to this issue. Moreover, the diverse manufacturing processes employed by different companies to produce nanofertilizers result in inconsistencies in product quality, complicating farmer's decisions when selecting suitable products. This lack of clarity presents challenges for corporations striving to meet essential standards in product development.

Fellet et al. (139) showed that variability in nanoparticle size, shape and composition is an essential concern stemming from the lack of standardization in NF preparation. Synthesis of nanofertilizers using methods involving various nanoparticles with different characteristics, significantly impact their efficacy in delivering nutrients to plants. Furthermore, variations in synthesis can lead to nanoparticles with varying compositions, affecting their stability, biocompatibility and toxicity.

It is crucial to establish guidelines, protocols and standards for their preparation, characterization and evaluation of NP. These measures would ensure consistency and high quality in the nanoparticles produced, facilitating the effectiveness. International organizations and national regulatory agencies should collaborate to develop safety guidelines and regulatory frameworks for NFs, ensuring their safety for agricultural use (140).

Long term effects on soil health and ecosystems

Though nanofertilizers are intended for precise nutrient delivery, some nanoparticles may persist in the soil. Prolonged exposure to these particles could potentially alter soil characteristics and nutrient cycling processes, impacting plant growth and ecosystem dynamics. Moreover, the continual use of nanofertilizers might influence soil microbial communities. Microorganisms are crucial for nutrient cycling, organic matter decomposition and soil fertility (141). Changes in microbial diversity and activity resulting from nanofertilizer application could disrupt these vital soil processes, leading to shifts in nutrient availability and overall soil health over time.

Additionally, the interactions between nanofertilizers and other soil components, such as organic matter and clay minerals bring long-term effects on soil health. These interactions could influence the stability, mobility and accessibility of nanoparticles to plants and microorganisms. Another significant concern with nanofertilizers is their potential impact on non-target organisms. Research indicates that exposure to nanoparticles can have adverse effects on various organisms including insects, fish and birds (140). These impacts may encompass disruptions to reproduction, growth and development, potentially resulting in decline in population sizes. Moreover, the influence of nanofertilizers on beneficial microorganisms, such as N fixing bacteria and mycorrhizal fungi, remains inadequately understood, necessitating further research to evaluate the ecological risks associated with nanofertilizer utilization (142).

Conclusion

Limited resources in farming and the harmful effects of using conventional fertilizers led to search of alternate/better fertilizers and smarter ways to use them. The existing levels of nutrient use efficiency in global crop production are neither sustainable nor acceptable. Nanofertilizers are a new solution for sustainable farming. They can help improve food security, protect the environment and increase crop production. Nanofertilizers can prove to be better option than regular fertilizers. This is because they possess unique features like a high surface area and slow nutrient release which help in delivering nutrients more efficiently, reducing harm to the environment and promoting sustainable farming.. Their application reduces nutrient loss and improves nutrient use. They also help plants grow better by boosting photosynthesis, assisting in seedling development and developing stress resistance. Using nanofertilizers comes with challenges. High amounts of some nanofertilizers can harm soil microbes and enzyme activity. Their effectiveness depends on factors like coating, particle size, soil type and pH. More research is needed to find the right doses and understand their impact on crops. There are also concerns about toxicity, a lack of research and regulations, and their higher cost compared to regular fertilizers. They offer one of the best solutions for sustainable agriculture by reducing chemicals.

Future Perspectives and Research Directions

Nanofertilizers offer numerous benefits but face challenges like high costs, limited farmer awareness, uncertain long-term effects and strict regulations. Traditional farming practices make it difficult to introduce new technologies, highlighting the need for awareness programs on nanocarrier-mediated fertilizer delivery. Smart farming tools, including nanosensors, can improve efficiency by enabling real-time soil nutrient monitoring and precise fertilizer application. Developing biodegradable, controlled-release formulations will optimize nutrient uptake and minimize environmental impact. Precision farming techniques, such as drones, can help assess nutrient levels and prevent overuse. An assessment of nanofertilizers can provide insights into their productivity, environmental impact and effects on food chains.

Field validation is crucial to address stakeholder concerns and build confidence in their effectiveness. Future research should focus on understanding their environmental fate, toxicity and biodegradability. Potential risks associated with nanoparticles in agriculture must be evaluated for long-term sustainability. Establishing standardized regulations and clear legal frameworks will ensure their safe and efficient use. Collaboration between researchers, policymakers and farmers is essential to promote responsible nanofertilizer adoption.

Strengthening research on nano–bio interactions will help assess their impact on soil health and ecosystems. Government incentives and subsidies can encourage farmers to adopt nanofertilizers in a cost-effective manner. Education and training programs should be conducted to enhance farmers' knowledge of nanotechnology in agriculture. Sustainable nanofertilizer development requires balancing productivity with environmental and health safety. Strong regulatory frameworks and comprehensive risk assessments will support their safe and effective use in modern agriculture.

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Authors' contributions

ASG contributed to the manuscript's conceptualization, literature review and drafting. KP provided critical insights and revisions to improve the scientific rigor of the review. PP and TK were responsible for acquiring and analysing relevant literature. SR and SU contributed to the organization and refinement of the manuscript, ensuring clarity and coherence. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflicts of interest.

Ethical issues: None

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