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REVIEW

Aspects of the Current and Prospective Sustainable Usage of Nanofertilizers in Agriculture and Their Effects on Health of the Soil: an Updated Review

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Abstract
By 2050, the global population is projected to reach nearly 9.6 billion, increasing demand for agriculture and placing more strain on the planet's natural resources. Occurrence of widespread nutrient shortage in soil resulting from intensive cropping has expedited great economic losses for farmers. Application of conventional fertilizers on a large scale to boost agricultural output is not a lengthy solution because these are seen as two-edged swords due to their potential to harm soil structure, mineral cycles, soil biota, plants, and ultimately cause heritable mutations in succeeding generations while increasing crop productivity. The development of nanoagrochemicals, such as "nanopesticides" and "nanofertilizers," has been a major focus of research in the field of agriculture-related nanotechnology. In particular, the basic issues with conventional fertilizers that influence agriculture could be systematically addressed by nanotechnology. The purpose of this paper is to update readers on the status of nanotechnology in this domain and to highlight prospects for the application of nanotechnologies in the field of fertilizers and plant nutrition. The following themes will mostly be investigated in this review: comparison of results of application of conventional and nanofertilizers, updated role of nanofertilizers in agriculture, green synthesis of nanoparticle, implications of nanoparticles on soil health, and current barriers and gaps in use of nanotechnology for crop production. In addition, the future challenges have also been discussed in the present review article.

Keywords Nanofertilizers · Biogenic nanoparticles · Green synthesis · Conventional fertilizers · Phytotoxicity · Earthworms

1 Introduction

The production of an abundance of food to feed an expanding population is one of the key problems faced by the world for which some of the substitutes such as use of sustainable management techniques are proving to be mandatory (Chippa and Joshi 2016). Scarce resources and a rapidly expanding human population, which is predicted to exceed 9.6 billion by 2050, necessitate the development of highly efficient agriculture while reducing global poverty and hunger. Mineral fertilizers supply nutrients to plants for optimal output. However, current crop-farming techniques cannot meet soaring food demand without relying heavily on chemical fertilizers (Zhang et al. 2015). The global consumption of chemical fertilizers (N + P + K) has been increased from 46.31 million MT in 1965 to 190.81 million MT in 2019 (FAO 2022). In India, the total consumption of N, P, and K at the rate of 20.40, 8.98, and 3.15 million MT, respectively during 2020–2021 represented growth of 6.8, 17.2, and 21%, respectively, over 2019–2020 (FAI 2021).

Fertilizers are necessary for crop growth because they provide key nutrients for growing crops, raising crop yield, and quality. Crop macronutrient use efficiency, on the other hand, is extremely low, with nitrogen (N), phosphorous (P), and potassium (K) use efficiency ranging from 30–60, 10–20, and 30–50%, respectively (Ha et al. 2019). It signifies that 50–70% of N and K fertilizer and 80–90% of P fertilizer could not be assimilated by crops and are reintroduced into the environment (Ha et al. 2019). Chemical fertilizer residues not only cause health hazards, but also impair ecosystem sublevels including soil microbial flora, parasites,

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and the marine environment via runoff and eutrophication (Conley et al. 2009).

The synthetic chemical fertilizers are known to be a possible source of heavy metals and a source of natural radionuclides (Savci 2012). They mostly contain heavy metals like Hg, Cd, As, Pb, Cu, and Ni, as well as naturally occurring radionuclides such ^{238}U, ^{232}Th, and ^{210}Po (Sonmez et al. 2007). Ionizing radiation from these radionuclides is emitted into the air by the factories that produce fertilizer and the farmers who apply fertilizer directly to the soil. Long-term exposure to these radiations emitted by fertilizers has the potential to cause cancer in people, as a result, there should be global awareness of these radiation concerns (Sonmez et al. 2007). In addition to affecting food security, using more chemical fertilizers degrades soil, emits greenhouse gases, contaminate water, and also the excess use of fertilizers leads to its entry into the food chain via absorption from soil (Wang et al. 2016). Additionally, overuse of chemical fertilizers raises the cost of production and diminishes growers' profit margins (Zulfiqar et al. 2019). Nanotechnology delivers disruptive, game-changing discoveries that can offer quick answers and solutions to problems affecting our society, the environment and agricultural production, as opposite to gradual improvements by other technologies (Zhao et al. 2019). Nanofertilizers are the most recent and technologically sophisticated method of progressively releasing nutrients into the soil in a regulated manner. They have the ability to break seeds and increase nutrient accessibility to the plants, hence enhancing economic yield. Due to their capacity to cover a large specific surface area, nanomaterials have advantages over other nutritional salts in terms of supporting crop growth and by preventing eutrophication and promoting agricultural sustainability, nanofertilizers have recently made it possible for significant improvements to be made in quality of agricultural production (Basavegowda and Baek 2021). Therefore, it is necessary to transform "traditional farming techniques" into "smart farming practices" by using cutting-edge technologies like nanotechnology for the creation of environmentally friendly crops production systems.

Tiny molecules called nanoparticle/nanoparticles (NP/NPs) range in size from one to one hundred nanometers (nm) and have a variety of physiochemical characteristics as compared to the bulk materials (El-Saadony et al. 2019, 2020; Reda et al. 2021). The NPs could increase fertilizer use efficiency of crop because the nano-scales enables their absorption by stomata and the trichome base; therefore, showing a positive effect on plant growth at lower doses than the bulk forms (Herrera et al. 2016). Furthermore, NPs have a large surface area, high capacity for absorption, and an accessible delivery system (Rameshaiah et al. 2015; Chhipa and Joshi 2016). On the basis of plant nutritional needs, nanofertilizers are categorized as macro-nanofertilizers, micro-nanofertilizers, nano-biofertilizers, nano-particulate fertilizers, and nano-coatings or packaging materials. The pertinent features of nanofertilizers are (1) delivery of appropriate nutrients to the plant, (2) reduction in cost of cultivation, (3) sustainable sources of plant nutrients, (4) effective fertilization, (5) essential reduction of environmental pollution (Guru et al. 2015).

Commercial applications of nanoformulations in agriculture include the utilization of, Cu, Mn, Mo, Zn, Fe, and C nanotubes as well as their oxides (Trobisch and Schilling 1970; Mahajan et al. 2011; Nekrasova et al. 2011; Ghafariyan et al. 2013; Pradhan et al. 2013; Taha et al. 2016; Alshaal and Ramady 2017). The behavior and impact of NPs on plants have been examined in a number of reviews but not a significant amount of information has been produced regarding the soil. Therefore, in order to fill this gap in the literature, this study tries to gather the information on different types of NP-based nanofertilizers, the manner in which plants absorb them, an updated comparison of conventional versus nanofertilizers in agriculture, updated research work of researchers on use of nanofertilizers in agriculture, biogenic or green synthesis of nanofertilizers, ways in which NPs affect the soil health and existing deficits and constraints in use of NPs. This literature review marks the first to combine any of these notions into a single piece of writing, as far as we know. In the agricultural sector, nanotechnology is a fast expanding subject that is almost always reaching new heights. There are numerous frequent advancements in this technology. It is therefore important to inform researchers of any new developments in nanotechnology. Although, it directly benefits soil and plants, as with many technologies, it also has unforeseen consequences. Therefore, through this article, we also intend to discuss negative effects related to use of nanofertilizers in order to keep researchers up to date.

2 Classification of Nanofertilizers

The nanofertilizers on the basis of mineral nutrients present in them, categories and mode of action can be divided into eight types (Fig. 1) (Salama et al. 2021).

2.1 On the Basis of Nutrients

A categorization of nanofertilizers predicated on their nutrient content is macro-nanofertilizers, micro-nanofertilizers, nano-biofertilizers, nano-particulate fertilizers, and nano-coating materials. Macronutrient nanofertilizers contain macronutrients (e.g., NPK) coupled with NPs to provide the plants with a specific amount of nutrients and lessen the high volume requirements (Prasad et al. 2017), whereas micro-nanofertilizers contain micronutrients (e.g., Zn, Cu, and Fe). Micronutrients are requisite for maintenance of metabolic processes in the plants and which the

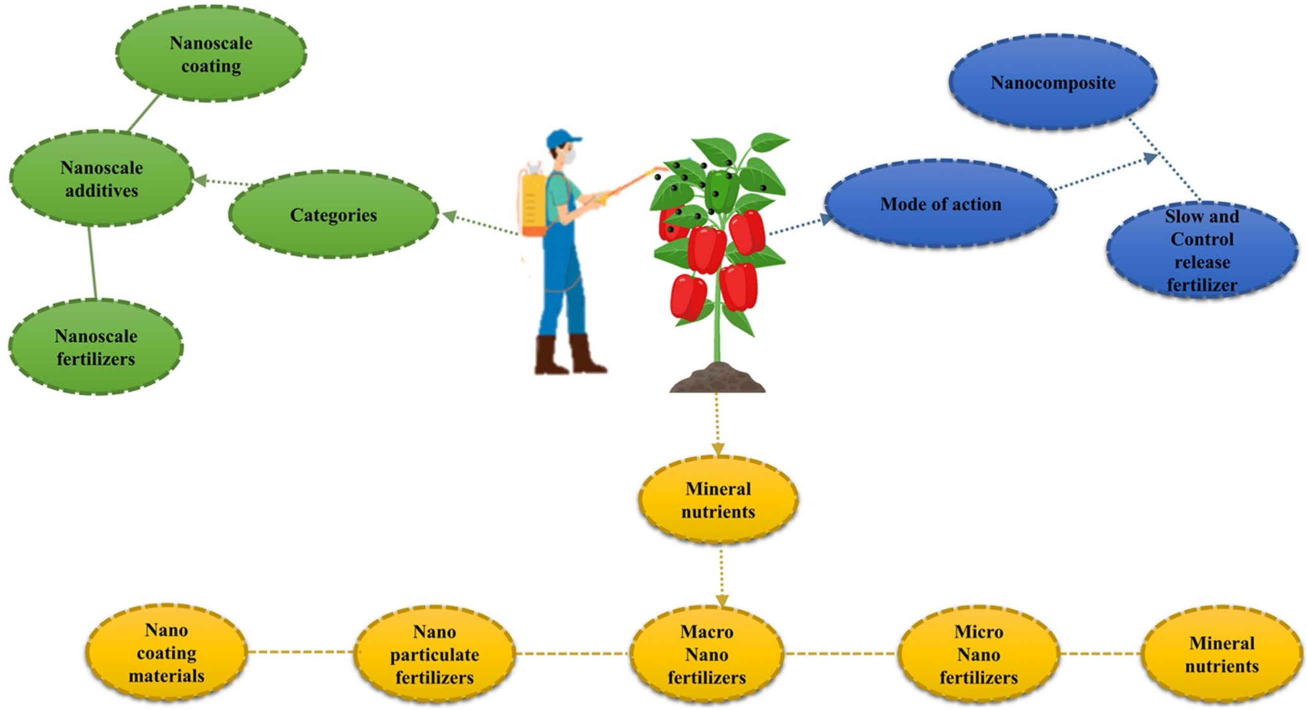

Fig. 1 Classification of nanofertilizers

plant needs in miniscule quantities (Prasad et al. 2017). Nano-biofertilizers are fabricated of interaction between NPs and microorganisms. For instance, the interaction of gold NPs with rhizobacteria that encourage plant development results in nano-biofertilizers (Prasad et al. 2017). The amalgamated formulation of NPs and nanotubes create novel sophisticated substances that are active in nature and serve as nanofertilizers. These are known as nanoparticulate fertilizers (Rastogi et al. 2017). The light layer substance known as nano-coating extends the shelf life of products (Sharma et al. 2020).

2.2 On the Basis of Mode of Action

The term controlled release nanofertilizers are frequently used for nanofertilizers where it is possible to regulate the rate, rhythm, and release of nutrients through preparation (Trenkel 2010). On the contrary, slow release nanofertlizers have nutrient discharge that is slower than other types; however, it is impossible to regulate the pace, pattern, or duration of nutrient release (Trenkel 2010; Jia et al. 2020). A composite material with at least a single dimension that is nanoscopic in size, i.e., around 10^{-9} m is known as nanocomposite. Nanocomposites are known to reveal rare properties because they are high-performance materials (Rathod 2020).

2.3 On the Basis of Different Categories

Nanoscale fertilizers are formulations having powder or fluid consistency containing desired nutrient elements at nanoscale dimensions (Liu and Lal 2016). In nanoscale additives, to create a large product, NPs are included (> 100 nm scale). These NPs may be an auxiliary material added for a concomitant purpose, such as soil/plant pathogen control or water retention (Mastronardi et al. 2015). Nanoscale coatings are nanoporous materials or nanothin sheets that impede the regulated release of nutrients. Zeolites, clays, and thin polymer coatings are a few examples (Mastronardi et al. 2015).

3 Uptake of Nanofertilizers by Plants

3.1 Foliar

Physiology of plant plays a crucial role in uptake of nanofertilizers (Schwab et al. 2016). Through endocytosis, the NPs might enter the plant cell from the cell membrane (Samaj et al. 2004; Etxeberria et al. 2006). The diameter of the stomata, which varies from 5 to 20 nm, determines the NPs' access into the plant cell wall (Fleischer et al. 1999). They can also enter the plant cell through base of the trichrome. Two pathways, apoplastic and symplastic pathways, are used by plants to translocate NPs. Macromolecules migrate through the outer membrane and the intercellular spaces through the apoplastic route. On the contrary, in the case of symplastic pathway, the movement occurs by plasmodesmata (of the plasma membrane's inside).

Hong et al. (2014) reported absorption of CeO_2 NPs via cucumber leaves and then its spread throughout plant tissues. According to Abd El-Azeim et al. (2020), NPK-containing nanofertilizers should be used topically rather than edaphically to increase potato yield. Application of silver NPs on leaves leads to its absorption and transportation by plant tissues of lettuce as stated by Larue et al. (2014).

3.2 Roots

Nanoparticles reach the xylem by penetrating the epidermis of the root. They travel through the xylem to the plant's aerial components. They do so via pores in the cell wall having a size range between 3 to 8 nm (Zulfiqar et al. 2019; Rajput et al. 2020; Ali et al. 2021). The entry of NPs into roots can also be significantly influenced by the root tip meristems. NPs must break through cell walls and plasma membranes to enter the epidermal layers of roots and then they may go on to penetrate the vascular tissues (xylem).

Tomato roots were found to absorb gold NPs of 3.5 nm; however, they were unable to take in 18 nm NPs (Zulfiqar et al. 2019). Conventional fertilizers are known to pollute soil and water as much of the nutrients from the applied fertilizers are lost due to leaching. Furthermore, certain agricultural chemicals cause climate change by releasing greenhouse gases (Rochette et al. 2018). Torney et al. (2007) reported that the application of mesoporous silica NPs to the soil regulated the intracellular release of chemicals in protoplasts. *Arabidopsis thaliana* were reported to uptake spherical silica NPs (through roots) of size 14 to 200 nm (Slomberg and Schoenfisch 2012).

4 Agriculture and NPs

Agriculture is known as "economic backbone" of emerging nations as it supplies food for improved living conditions worldwide (Pouratashi and Iravani 2012; Mittal et al. 2020). Ever increasing population of our globe is anticipated to increase its food demand by approximately 70% in 2050 (Bindraban et al. 2018; Mandal and Lalrinchhani 2021). Therefore, to achieve global food security, it is essential to codify cutting-edge agriculture techniques with improved plant yield (Mandal and Lalrinchhani 2021). Due to their smaller size than bulk particles, nanoscale particles may well be absorbed with distinct dynamics, which has important advantages such as increased production, growth, and quality as given in Table 1. The utilization of nanofertilizers may increase the effectiveness of plants' nutrient delivery (Chhipa 2017) due to the fact that nanofertilizers enable targeted distribution, slow release of nutrients, and reduce chemical use (Kah et al. 2019). The reduced size of nanofertilizers enhances their surface-mass ratio which allows more absorption of nutrients by roots.

5 Conventional Fertilizers Versus Nanofertilizers

There are copious methods of delivery of conventional fertilizers to the crops. They are generally applied either by sprinkling or dispersing. The ultimate concentration of the fertilizers reaching the crop, however, is one of the crucial criteria that determine the method of application. In a real-world scenario, losses through chemical leaching, washout, evaporation, hydrolyzed by soil moisture, and photolytic and microbiological breakdown result in concentrations that are significantly lower than the lowest intended concentration reaching the targeted site. According to reports, traditional fertilizers lose between 40 and 70% of their N, 80 to 90% of their P, and 50 to 90% of their K content before reaching the crop, causing long-term and significant economic losses (Ombodi and Saigusa 2000).

Chemical fertilizers and pesticides have caused these issues by being used repeatedly, which negatively impacts the soil's natural nutritional balance (soil health). To reduce the danger of environmental damage, it is crucial to redesign the use of chemical (traditional) fertilization. Suitably, it may be advantageous to adopt alternative fertilizing techniques that can deliver essential nutrients for plant development and productivity while preserving the soil's health and keeping a clean environment (Miransari 2011). Table 2 shows comparison of conventional fertilizers and nanotechnology based fertilizers.

6 Green Synthesis of NPs

6.1 Chemical Synthesis Versus Green Synthesis of NPs

The NPs are made utilizing a variety of techniques, including physical, chemical, and biological ones. Numerous physical and chemical processes, such as hydrothermal synthesis, sol–gel formulation, laser ablation, and lithography, need specialized tools and trained workers. Furthermore, these are hazardous to health and have toxic effects on environment (Iravani 2011; Darroudi et al. 2014). One of the most popular approaches is biological synthesis, often known as the biogenic or biomimetic pathway. High raw material availability, lower costs, low energy usage, and less health and

Table 1 An updated results of different macronutrient and micronutrient-based nanofertilizers in agriculture

S.no	NP/s	Concentration	Mode of application	Crop	Observations	References
1	Nitrogen, phosphorous and potassium	100 mg L^{-1}	Foliar	*Solanum lycopersicum*	Increased output and growth rate	Panda et al. (2020)
2	Zinc oxide	160 mg Zn kg^{-1}	Soil	*Glycine max*	Grain yield was increased and oxidative stress reactions were strongest	Tanha et al. (2020)
3	Ttanium dioxide	50 µg mL^{-1}	Seed	*Vigna radiata*	A higher rate of germination, longer seedlings, roots, and shoots were observed	Mathew et al. (2020)
4	Titanium dioxide	-	Foliar	*Triticum aestivum*	Influenced the jasmonic acid (JA) pathway	Ghosh and Bera (2021)
5	Phosphorous	60, 400, 500 mg kg^{-1}	Foliar	*Triticum aestivum*	A 40-day maturity period delay and 101.8% increase in grain production per plant were seen	Gomez et al. (2021)
6	Zinc oxide	-	Foliar	*Helianthus annuus* L	Decreased sodium ion concentration in leaves and increased carbon dioxide absorption and photosynthetic rates	Seleiman et al. (2021)
7	Molybdenum trioxide	20–40 mg L^{-1}	Foliar	*Phaseolus vulgaris* L	Proteins that were present in greater amounts in the seedlings compared to the blooming stage	Osman et al. (2020)
8	Titanium dioxide	20 and 30 mg L^{-1}	Foliar	*Oryza sativa*	Enhanced proliferation, decreased cadmium translocation, and reduced its toxicity	Shang et al. (2019)
9	Copper oxide	75–300 mg kg^{-1}	Soil	*Allium fistulosum*	Increased the contents of allicin and vital elements like manganese, iron, and nickel which improved the quality	Wang et al. (2020)
10	Zinc and iron	1.5 g L^{-1} and 2 g L^{-1}	Foliar	*Phaseolus vulgaris*	Zinc and iron increased leaf area, proline, and soluble sugar content and antioxidant enzyme activity	Grangah et al. (2020)
11	Cerium dioxide	100 mg L^{-1}	Soil	*Brassica oleracea*	Increased the cabbage head weight and chlorophyll content	Abdulhameed et al. (2021)
12	Nitrogen, phosphorous, and potassium	7.5 ml 10 L^{-1}	Foliar	*Ocimum basilicum* L	Increased plant growth, essential oil and seed production under high soil pH conditions	Alhasan (2020)
13	Silicon dioxide	0, 100, 500, 1000, 2000 mg L^{-1}	Hydroponics	*Glycine max*	Decreased the translocation and buildup of mercury (Hg) and lessened its harmful effects while promoting seedling development	Li et al. (2020)
14	Titanium dioxide	100 mg L^{-1}	Hydroponics	*Dracocephalum moldavica*	Improved synthesis of essential oils and antioxidant enzymes	Gohari et al. (2020)

Table 1 (continued)

S.no	NP/s	Concentration	Mode of application	Crop	Observations	References
15	Zin oxide	50 mL of 1500 ppm	Soil and foliar	*Solanum lycopersicum* L	Improved plant height, stem diameter, and dry weights	Perez Velasco et al. (2020)
16	Cerium dioxide	300 to 2000 mg L^{-1}	Hydroponics	*Fragaria × ananassa*	Lengthened shoots and roots by increasing the effectiveness of water and nutrient uptake	Dai et al. (2020)
17	Cerium dioxide	500 mg kg^{-1}	Soil	*Zea mays* L	Significantly impacted the root morphology and physiology of maize plants	Fox et al. (2020)
18	Copper oxide	0.01 and 0.025 mg mL^{-1}	Seed	*Lens culinaris*	Increased the root length, seedling vigor index and seed germination	Sarkar et al. (2020)
19	Magnetite	4 mg L^{-1}	Hydroponics	*Medicago falcata* L	Increased the root length and chlorophyll content	Kokina et al. (2020)
20	Ferric oxide	30–90 mg L^{-1}	Foliar	*Dracocephalum moldavica* L	Leaf area index, secondary metabolites like phenolics, flavonoids, and pigments like anthocyanin were all increased	Moradbeygi et al. (2020)
21	Titanium dioxide	500–2000 mg kg^{-1}	Soil	*Triticum aestivum*	Enhanced stomatal activity, transpiration rate, antioxidative enzymes, total chlorophyll, relative water content, and dry weight of the seedlings	Faraji and Sepehri (2020)
22	Iron	25–100 mg kg^{-1}	Soil	*Triticum aestivum*	Good development and physiology, improved photosynthesis, high levels of iron, and low levels of cadmiun	Adrees et al. (2020)
23	Zinc oxide and sulfur	50–150 mg L^{-1} (ZnO); 150–300 mg L^{-1} (Si NPs)	Soil	*Mangifera indica* L	Higher rates of nutrient absorption, carbon uptake, and plant growth	Elsheery et al. (2020)
24	Cerium oxide	500 mg L^{-1}	Seed	*Gossypium hirsutum* L	Reactive oxygen species (ROS) levels were reduced, root development metrics were enhanced and triggered to tolerance pathways, including improvement in homeostasis	An et al. (2020)

Table 2 Comparison of fertilizers using conventional methods and those based on nanotechnology

S. no	Crop	Results	References
1	Rice	Grain yield and milled rice yield of treatments receiving nano nitrogen and cooking and eating quality of rice grains supplied with nano potassium were significantly higher than that of their conventional forms	Valojai et al. (2021)
2	Potato	The greatest rate of vegetative and yield features was recorded by fertilization with nanofertilizers, which was much higher than individual application of standard macronutrient fertilizers	Juthery (2019)
3	Lupine	Highest growth parameters were obtained with foliar application of conventional primary macronutrient fertilizers; however, nano nitrogen, phosphorous, and potassium fertilizers showed highest fresh and dry weight of lupine The lowest values of fresh and dry weight of lupine were recorded with soil application of conventional NPK fertilizers	Hemdan et al. (2020)
4	Olive	Fruit yield and traits were better under potassium nitrate treatment, whereas the quality of olive oil was more stable under nano-chelate potassium foliar application	Vishekaii et al. (2022)
5	*Caesalpinia bonducella*	In comparison to control plants, the chlorophyll contents increased by 5–28% with traditional fertilizers and by 30–80% with the application of NPs When compared to other traditional fertilizers, zinc oxide NPs produced the highest growth and yield	Khalid et al. (2022)
6	Strawberry	Fertilization with nitrogen fertilizer (conventional) increased yield, but resulted in fruits with leafy green flavor, less flowery, and fruity notes resulting in lower fruit aroma quality when compared with nano-fertilized strawberries	Weber et al. (2021)
7	Wheat	Foliar application of nanofertilizers along with recommended dose of fertilizers (RDF) improved yield as well as soil microbial population and microbial biomass C as compared to sole application of RDF	Meena et al. (2021)
8	Snap bean	Comparing nano calcium phosphate to conventional phosphorous, the snap bean plants' shoot and root dry weights, shoot and root nutritional content, yield components, and crude protein percentage in pods all rose considerably The maximum increase was attained with a soil treatment of 20% nano calcium phosphate and a foliar spray of 5%	Abd El-Ghany et al. (2021)
9	Sesame	Co-application of nitroxin (biofertilizer) + 50% urea (conventional) + potassium-nano-chelate topically, improved the quantitative and qualitative features by improving growth, physiological, and biochemical characteristics along with moderating the negative effects of severe water stress	Khorami et al. (2020)
10	Peppermint	Macronutrients and iron concentrations were at their highest possible levels with application of 50% conventional fertilizer + nano-chelated fertilizer as compared with sole application of conventional and sole application of nanofertilizer Furthermore, the use of 50% chemical fertilizer + 50% nano-chelated fertilizer resulted in the maximum peppermint dry matter accumulation, essential oil content and essential oil yield	Ostadia et al. (2020)
11	Date palm	Foliar application method surpassed adding via soil in vegetative growth, whereas the methods of application produced non-significant differences among other traits Fertilizer N applied as NPs at a rate of 60% RDF via soil application recorded highest yield as compared with conventional fertilizers	Abd EL-Rahman and Abd-Elkarim (2022)
12	Capsicum	In comparison to solitary application of conventional fertilizers, the combination of 100% conventional fertilizers and 0.5 g L^{-1} of nano-micronutrients produced the maximum yield and capsaicin content	Ahmed and Abdelkader (2020)
13	Tomato	Nano-iron fertilizer application increased tomato output by 11% in comparison to conventional-iron and chelated-iron fertilizers	El-Desouky et al. (2021)

environmental risks are a few benefits of green synthesis. Additionally, compared to complex (physical and chemical) approaches, infrastructural and chemical needs for biological processes are virtually nonexistent (Verma and Bharadvaja 2022).

6.2 Mechanism Behind Green Synthesis of NPs

Green nanomaterials can be produced using various biological routes such as plant-mediated, bacteria-mediated, actinomycetes-mediated, and fungi-mediated. Selecting an eco-friendly, affordable, and straightforward methodology is crucial given the large range of NP production processes available. Here, a thorough discussion of the generalized approach of synthesis of plant-mediated NPs is presented. The mechanism for green NP production is depicted in Fig. 2. The phytochemicals which are known to be present in the plant extracts (terpenes, quercetin, and phenolics) function as a reducing agent, converting metal precursors to metal NPs. These phytochemicals can serve as both reducing and stabilizing agents because they are antioxidants and nontoxic. These reducing agents (phytochemicals) are present in different concentration in different plant tissues. As a result, the composition of the leaf extract plays a crucial role in the creation of NPs (Mukunthan and Balaji 2012). After being reduced by plant extracts (Fig. 2), the metal ions undergo three steps of encapsulation as an organic coating for their stability. The first stage, known as the "activation phase," entails metal ion reduction and decreased metal ion nucleation. The second phase is "growth phase" which brings about the stability of NPs and the third phase is the "termination phase" that consists of formation of NPs (Love et al. 2015). Through the action of phytochemicals, metals like Cu, Ag, Au, Ti, Zn, Fe, and Ni produce their metal oxides. The linking of metal ions and creation of a distinct shape are the final effects of the production of oxygen (Singh et al. 2018). X-ray diffractogram, energy dispersive spectrometry, and scanning electron microscope techniques are used to determine the size and form of the NPs.

6.3 Green NP Production Process

Five hundred milliliters of distilled water is combined with 10 g of the plant's dry matter to create the plant extract. The resultant mixture is then heated to 90 °C on a thermal stirrer for 30 min. The solution obtained is passed through a fine filter (Whatman no. 1). To prepare any metal salt NPs say Zn, 1.83 g zinc acetate (molecular mass of zinc acetate), using an electric stirrer is dissolved in 100 ml of water and agitated for 10 min. Then, in 100 ml of plant extract, 100 ml of metal salt is mixed (for example, basil plant extract) and for 15 min, the resulting mixture is immersed in a hot water bath at around 60 °C. Likewise, to make green manufactured Cu, copper sulfate salt, is used and for Fe, iron sulfate is used (Abbasifar et al. 2020). The NPs produced by above method can be now used for crop production. Different NPs produced using plant extracts and the results obtained are depicted in Table 3.

7 Implications of NP Buildup on Soil Health

7.1 Effect of NPs on Biological Properties of Soil

It was shown that soil organic matter (SOM) adsorbs NPs easily, hence boosting their mobility in porous mediums and improving their stability in aqueous solutions (Xie et al. 2008; Johnson et al. 2009). According to the findings of Nyberg et al. (2008), fullerene NPs had minimal effect on the microbiota and their functions in soil. It has been

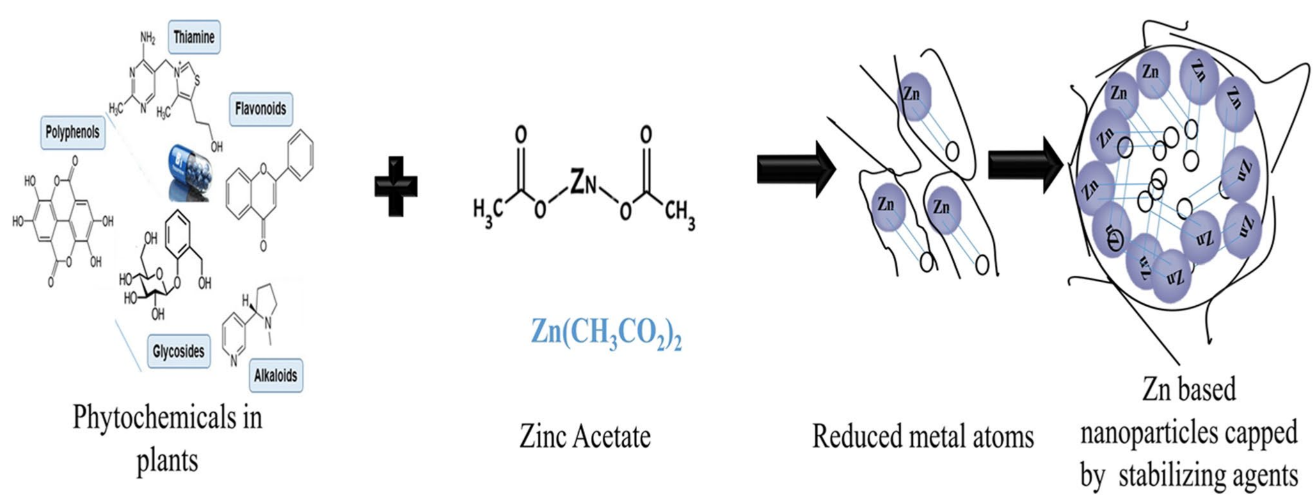

Fig. 2 Mechanism of green synthesis of NPs

Table 3 Plant-based green production of nanofertilizers in agriculture and their results

S. no	NP/s	Plant used	Part used	Results	References
1	Zinc oxide	*Punica granatum*	Fruit peel	Proven their compatibility in the tetrazolium salt assay using VeroE6 cells with higher cell viability	Abdelmigid et al. (2020)
2	Silver and copper oxide	*Catharanthus roseus*	Leaves	The heavy metal removal capability of silver was superior than copper. And both had bacteriocidal effect against *S. aureus*	Verma and Bharadvaja (2022)
3	Zinc and copper	*Ocimum basilicum*	Leaves	Increased antioxidant activity, flavonoid content, and total phenolic content	Abbasifar et al. (2020)
4	Potassium	*Musa* sp.	Peel	For tomatoes and fenugreek, increasing the dosage of banana peel extract increased the germination percentage	Hussein et al. (2020)
5	Zinc oxide	*Costus pictus*	Leaves	Demonstrated elevated levels of antimicrobial property against gm-positive bacteria *B. subtilis* and *S. paratyphi* (gm-negative bacteria)	Suresh et al. (2018)
6	Silver	*Capparis zeylanica* L	Leaves	Admirable antimicrobial activity against pathogenic microorganisms	Nilavukkarasi et al. (2020)
8	Zinc oxide	*Fragaria ananassa*	Leaves	Comparing this procedure to other synthesis techniques, it was more economical, safe and environmentally benign	Bayat et al. (2021)
9	Titanium dioxide	*Chenopodium. quinoa*	Leaves	Good antifungal response against wheat rust	Irshad et al. (2020)
10	Zinc oxide	*Cassia auriculata*	Leaves	The antibacterial activity of green synthesized zinc oxide NPs showed strong response against bacterial pathogens	Ramesh et al. (2021)
11	Silve	*Citrus limetta*	Peel	Embattled pathogens such as *Micrococcus luteus*, Streptococcus *mutans, Staphylococcus epidermidis*, *S. aureus, E. coli*, and *Candida* spp.	Dutta et al. (2020)
12	Gold	*Eclipta alba*	Whole plant	Embattled pathogens like *E. coli*, *P. aeruginosa*, *B. subtilis*, *S. aureus*	Vijayakumar et al. (2020)
13	Silver	*Gomphrena globosa*	Leaves	Targeted pathogens *S. aureus*, *B. subtilis*, *M. luteus*, *E. coli*, *P. aeruginosa*, *Klebsiella pneumoniae*	Tamilarasi and Meena (2020)
14	Nickel oxide	*Citrus sinensis*	Leaves	Gm-positive (*S. aureus*) and gm-negative (*E. coli*) bacteria were both susceptible to antibacterial activity of green NP	Khodair et al. (2022)

A. indica, *Azadirachta indica*; *M. luteus*, *Micrococcus luteus*; *S. aureus*, *Staphylococcus aureus*; *S. paratyphi*, *Salmonella paratyphi*; *E. coli*, *Escherichia coli*; *P. aeruginosa*, *Pseudomonas aeruginosa*; *B. subtilis*, *Bacillus subtilis*; *K. pneumonia*, *Klebsiella pneumonia*; *gm*, gram

confirmed that enzymatic activity and microbial biomass C and N in the soil are both decreased by multi-walled C nanotubes (Chung et al. 2011). Ge et al. (2011) evaluated the effects of ZnO and TiO_2 on soil microbial communities and showed that these NPs inhibited microbial mass in soil and their diversification. According to research by Pradhan et al. (2011), exposure to CuO and AgNPs reduced the pace at which leaves decomposed due to microbial activity. Additionally, modifications to the microbial communities' structure coincided with the decline in decomposition. Yang et al. (2009) revealed that humic substances' carboxyl (−COOH) and phenolic hydroxyl (−OH) functional groups form sturdy complexes with TiO_2NPs, altering the chemical compositions of humic substances. It was shown that AgNPs and Ag exhibited varying levels of toxicity on soil N-cycling microbes, including N fixing, nitrifying, and denitrifying bacteria (Yang et al. 2013).

Along with microbes, nematodes (ring worms) and earthworms are crucial for preserving the health of the soil. Studies that investigate the effects of NPs on nematodes are very rare and the majority of them concentrate upon the most well-known species of nematode, *Caenorhabditis elegans* (Starnes et al. 2019). For instance, Starnes et al. (2019) conducted an investigation on the toxicity of ZnONPs and their modified derivatives on *C. elegans* and discovered that both sulfidized and phosphatized

ZnONPs exhibited reduced nematode toxicity than pure ZnONPs. *Meloidogyne incognita*, a parasitic worm that causes root knots, has been the subject of several investigations. To illustrate the potent nematocidal impact of AgNPs on *M. incognita*, tomato roots dipped in AgNPs before being exposed to the nematode exhibited significantly decreased infection (Kalaiselvi et al. 2019). Earthworms (*Eisenia fetida*) are important for the nutrient cycle and the production of soil aggregations (Blouin et al. 2013). Hu et al. (2010) investigated the effects of the NPs on cell structures of the earthworm, the organelles were analyzed using transmission electron microscopy (TEM). The internal layer of the gut's cells included a lot of mitochondria (Fig. 3a). Some mitochondria had an aberrant appearance after being exposed to TiO_2NPs and ZnONPs for a week, including breakage, disarray, and reduction or complete collapse of the cristae (Fig. 3b and c). They also discovered that after being exposed for a week in the soil to ZnONPs and TiO_2NPs at a dosage of 5000 mg kg^{-1}, the gut cell's mitochondria were harmed. Additionally, they noted that ZnONPs were more harmful to earthworms and had a greater rate of bioaccumulation than TiO_2NPs. According to several studies (Barua et al. 2013; Heckmann et al. 2011), there was no or very little fatalities in earthworms subjected to AgNPs disseminated in the soil. AgNPs, however, negatively impacted reproduction by influencing variables such cocoon creation, incubation rate, and avoidance (Heckmann et al. 2011).

7.2 Effect of NPs on Physical Properties of Soil

The influence of NPs on the physical characteristics of soil has not been extensively studied (Ben-Moshe et al. 2013). The surface of the individual (soil) grains has noticeably changed due to the NPs (Ben-Moshe et al. 2013). Also, with a 1% loading, the NPs were built up on the surface of the grains in massive aggregates (> 100 nm) and the aggregates' NPs composition was verified by energy dispersive spectroscopy. Ben-Moshe et al. (2013) confirmed the reduced hydraulic conductivity and flow channel obstruction in the soil which may have resulted from the accumulation of NPs in the soil pores. In a separate research carried out by Nhallmark Bl (2017) , it was discovered that adding 6000 mg kg^{-1} of CeO_2NPs to the soil through repeated watering cycles had no effect on soil porosity, but that it had an impact on how water was distributed among different pore sizes and how much water was accessible to plants.

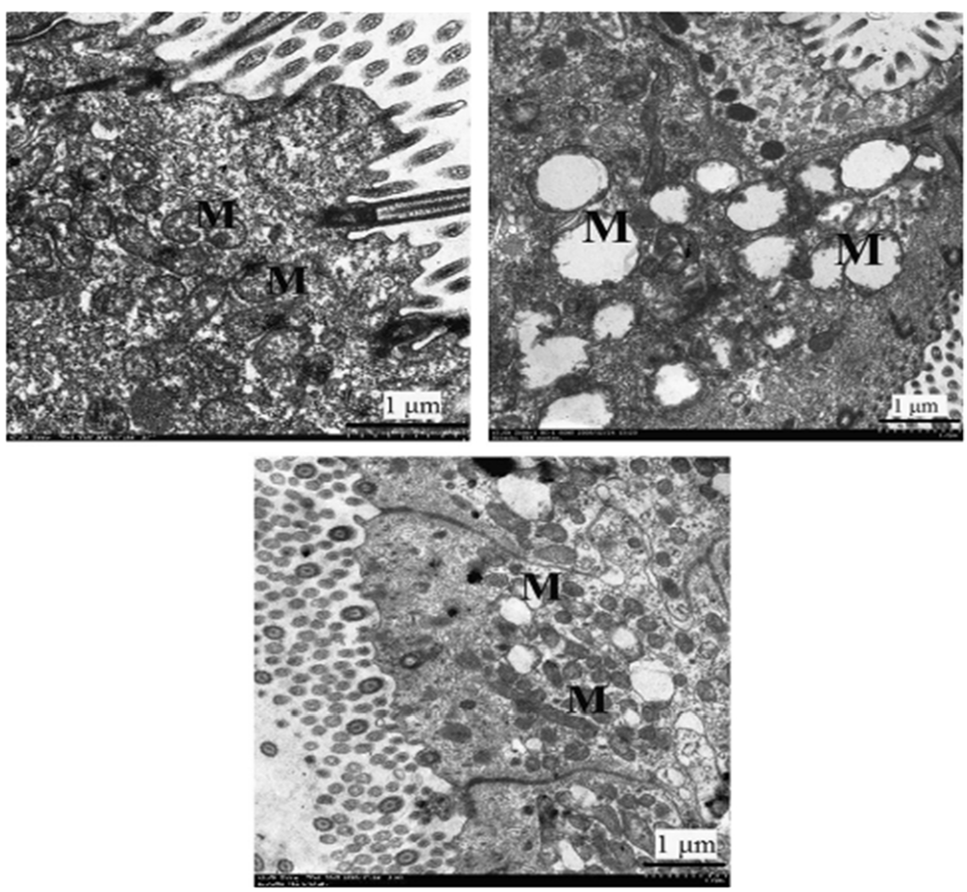

Fig. 3 (**a**) Transmission electron microscopy (TEM) images of cells in gut wall of *E. fetida* cultured in the artificial soil of the control, **b** 5 g kg^{-1} of titanium dioxide (TiO_2) and **c** 5 g kg^{-1} of Zinc oxide (ZnO). M represents the mitochondria. Reprinted from [Hu et al. (2010)] with permission of © (2010) Elsevier

7.3 Effect of NPs on Chemical Properties of Soil

As a crucial marker of soil chemical properties, soil cation exchange capacity (CEC) has a strong relationship to how well it can retain contaminants from the environment and nutrients for plants. According to De Souza et al. (2019), Fe_3O_4NPs boosted rhizosphere CEC in a study inside the greenhouse. According to Zhao et al. (2012a, b), ZnONPs have a great affinity for the colloids in soil. They have lower mobility over a range of ionic strengths and display greater sorption than ionic Zn^{2+}. The capacity of soil to keep its aggregate structure amid drought conditions was enhanced by raising the shrinkage of kaolinite (Fig. 4) clay by 8–17% after mixing it with 6% CuONPs or Al_2O_3NPs (Coo et al. 2016). Conversely, their effect on clay shrinkage was not apparent when the dosage of NPs was decreased to 0.5%. Interactions between NPs clay and NPs SOM (Ben-Moshe et al. 2013) may affect how readily available heavy metals are in soil. The accumulation of CeO_2NPs on the surface of 1:1 phyllosilicate mineral and kaolinite changed, its surface charge and for NPs to interact with clay, their surface charge is crucial (Sun et al. 2020). Elevated soluble Mg release was detected and was linked to soil CEC when 1–1000 mg kg^{-1} of TiO_2NPs, CeO_2NPs, or $Cu(OH)_2$NPs were added to soil (Conway and Keller 2016). In a separate research, adding Mn_2O_3NPs at a dose of 6 mg kg^{-1} showed reduction in NPK content in wheat shoots. The identical NPs, however, administered by foliar treatment either had no impact or raised the amounts of NPK in wheat shoots, demonstrating that the NP exposure pathway influenced plant nutrient absorption (Dimkpa et al. 2018). ZnONPs sprayed on mung beans increased plant P concentrations by

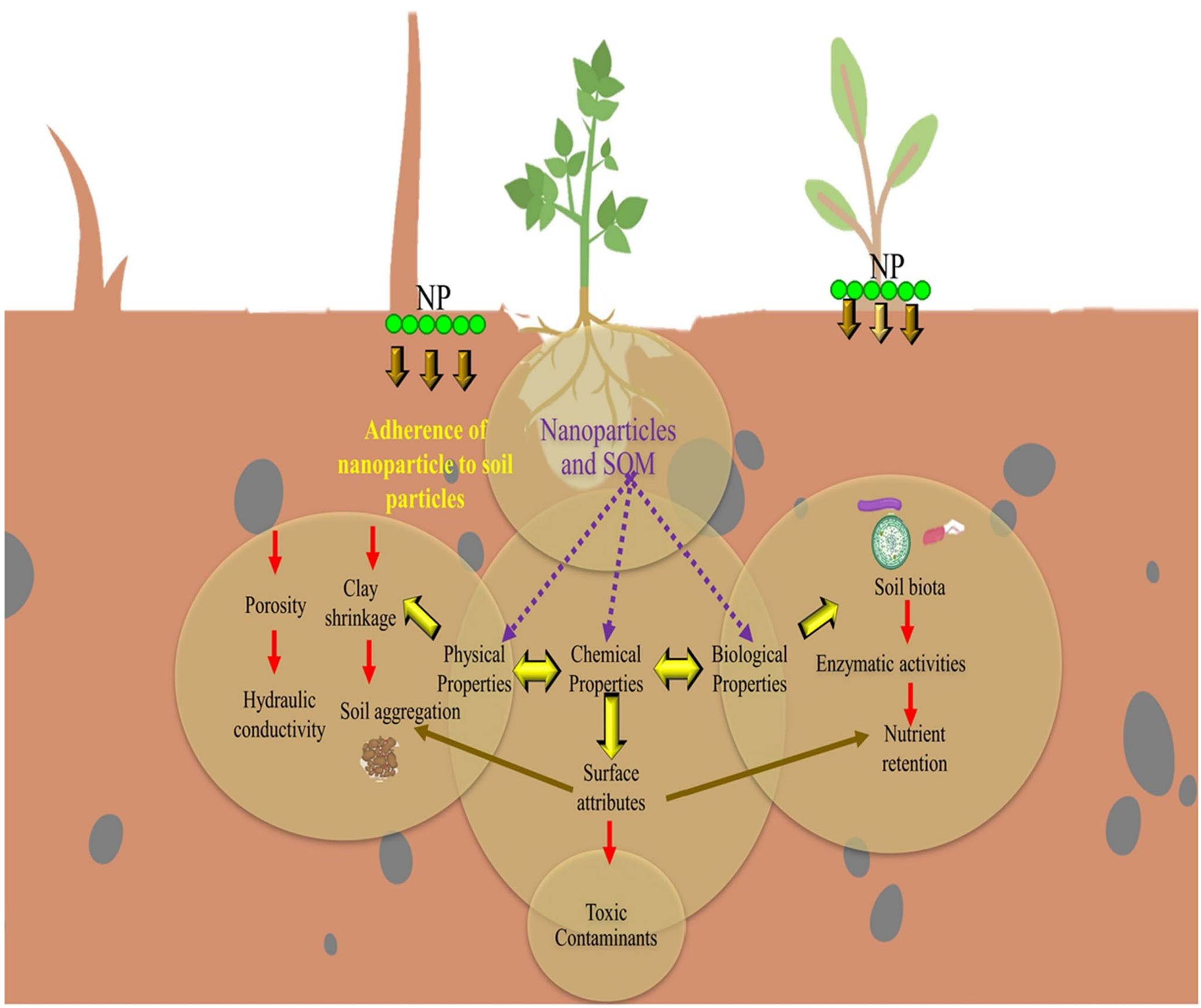

Fig. 4 Effect of NPs buildup on soil health. SOM represents soil organic matter

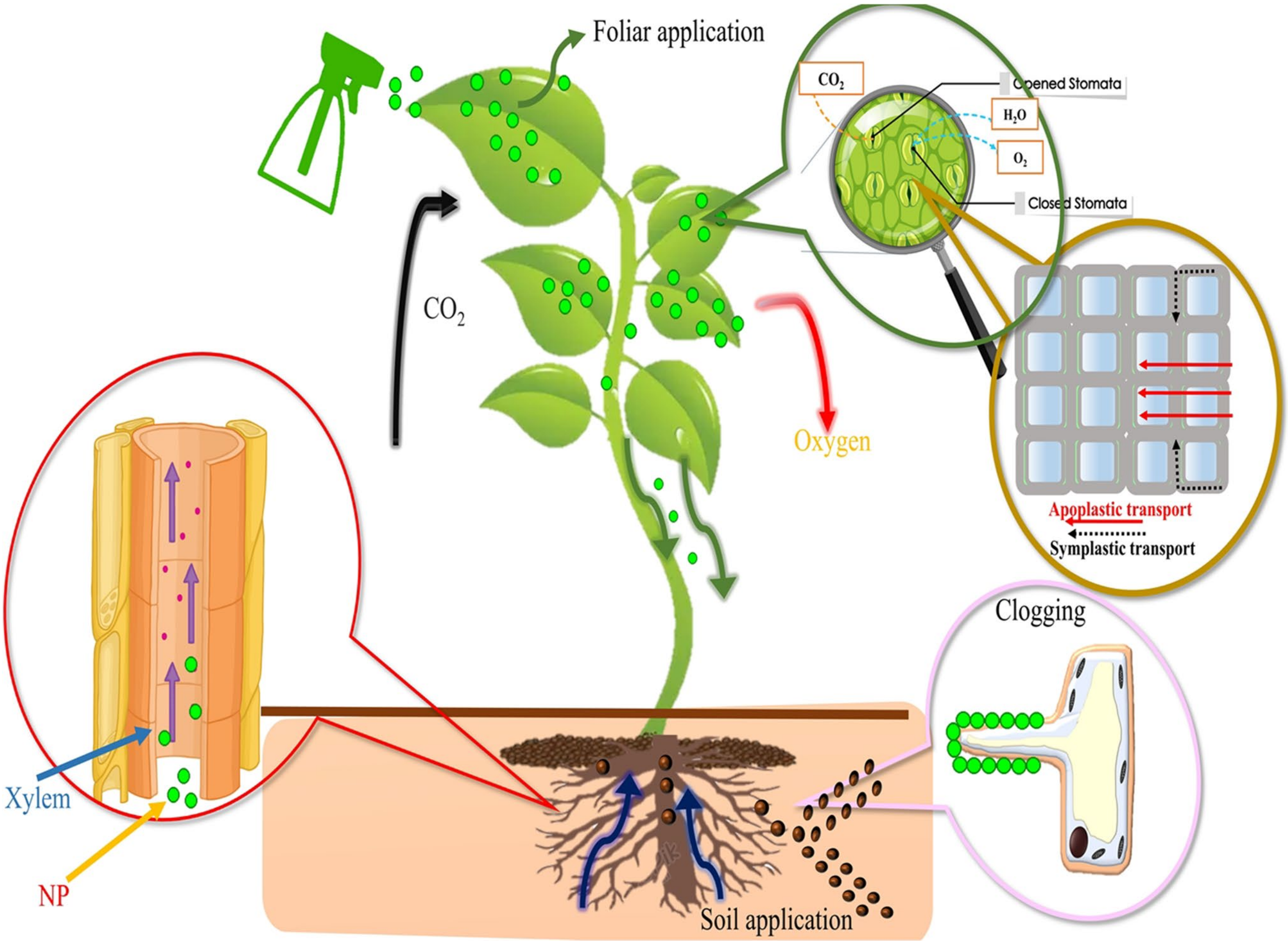

Fig. 5 The potential routes for NPs absorption and their negative effects. CO_2, H_2O and O_2 represents carbon dioxide, water and oxygen, respectively

11%when applied at 0.25 mg plant^{-1}, and this increase was attributed to improved activities of P-solubilizing enzymes in soil which in turn would have increased the availability of P (Raliya et al. 2016).

8 Existing Deficits and Constraints

To realize the full potential of nanotechnology, there are still several obstacles that must be addressed. The challenges are dealt below.

8.1 Plant Cell Structure

Xylem and phloem embodies the main pathway for translocation of absorbed NPs (Li et al. 2016; Avellan et al. 2019). However, the capacity of various plant species to absorb, assimilate, and translocate NPs may vary. For instance, *Cucurbita maxima* was found to ingest a significant amount of NPs and disperse them into various plant tissues, but *Phaseolus limensis* was not reported to have any NPs under the same circumstances (Lv et al. 2019). According to certain studies, nanomaterials with higher surface charges than those with lower or neutral charges were able to enter plant cells or tissues' membranes more easily (Wong et al. 2016; Zhai et al. 2015). Nevertheless, nanomaterials must first cross the plant cell wall before accessing the cell membrane. According to reports, NPs with relatively high diameters (> 40 nm) may also readily cross the cellular membrane and enter the tissues of plants (Wang et al. 2016; Zhai et al. 2015; Demirer et al. 2019). Lanthanide NPs can be delivered, according to recent research, by turning on the plant endocytosis system (Wang et al. 2019). It is still necessary to investigate how additional nanomaterials may be used with the endocytosis process.

8.2 Nanomaterials' Phytotoxicity

Nanoparticles may have a major reverberation on specific plants shortly after crossing plant cell walls or membranes;

these effects can be either lethal or therapeutic (Peng et al. 2012; Yin et al. 2015; Zhang et al. 2012). Nanoparticles have repeatedly been observed to be poisonous to plants (Zou et al. 2016). Heavy metals present in NPs may dissolve, release, and even metabolically transformed after being absorbed by plants, causing phytotoxicity (Rastogi et al. 2017). In contrast to their bulk equivalents, certain NPs are said to be more variable and unstable in the plant environment. Their tiny size, high surface-to-volume ratio, and high reactivity might all be contributing factors (Lv et al. 2019). However, some "stable" NPs could transform to unstable ones after their application. For instance, nano CeO_2 are often regarded to be stable (Zhao et al. 2012a, b); however, it has been discovered that they can be partially dissolved by the organic acids and chemicals the roots produce that are reducing in character (Lv et al. 2019; Zhang et al. 2012).

In addition, following transit, NP accumulation at the root surface or within plant parts may result in blockage and damage (Fig. 5) (Wang et al. 2016). They are also affected by the properties of growing media (Schlich and Hund-Rinke 2015). Different growth mediums (such as soil versus agar medium) interact with NPs differently, which might change their physical and chemical attributes and, as a result, their phytotoxicity (Zou et al. 2016). Fe_3O_4 NPs, for instance, were found to generate varying degrees of phytotoxicity in *Cucurbita mixta* plants cultivated in soil and sand (Zhu et al. 2008; Wang et al. 2011). Some growth medium characteristics, including pH, have enigmatic effects on NPs and may thus change their toxicity (Schlich and Hund-Rinke 2015; Yung et al. 2015). So, one emerging objective for NPs' potential uses is to better understand NPs' phytotoxicity and how they interact with the environment.

9 Conclusion and Future Prospects

The purpose of this review study was to offer some insight into the application of nanoparticles based nanofertilizers in agricultural production. Due to the pervasive nutrient deficit in agricultural soils, our findings, which are given here, indicate a decrease in crop output and significant economic losses in agriculture. Although providing nutrients with chemical fertilizers can lower economic losses by boosting agricultural output, its widespread usage is not a good long-term solution. As long as nanofertilizers are applied in specific concentrations and in accordance with crop requirements for minerals, they can be used as fertilizer carriers or controlled release vectors to create so-called "smart fertilizers" that improve nutrient use effectiveness and productivity without compromising the environment. The process of making desired nanoparticles from plants, or "biogenic synthesis," offers several environmental advantages over traditional approaches. A well-known advantage is the wide variety of raw materials that are readily available and the straightforward processes for making plant-based nanoparticles. Both in vitro as well as in vivo approaches can be utilized to deliver nanoparticles to plants. Due to the increased scientific understanding of how natural processes in soil and plants are influenced, the deployment of nano-based fertilizers in agriculture has the potential to be beneficial.

However, as there is little knowledge about how nanoparticles are absorbed, transported, and ultimately disposed off in plant systems, there are currently a number of moral and health concerns arising from the use of nanofertilizers in agricultural output. Although nanofertilizers have had interesting results in the world of agriculture, their market value has not yet been the primary consideration in how they should be used. When nanoparticles are applied via their metal oxide, it is possible for poisonous metal ions to be released and to build up in the soil, endangering human health in the process by reducing the health of the soil and plants. Consequently, before nanoparticles/nanofertilizers are used commercially, their possible impacts on human health must be thoroughly studied. Additionally, nanoparticles/nanofertilizer deployment protection and the investigation of their toxicity must be research priorities. Prior to the implementation of the use of nanofertilizers, it is essential to study the ecotoxicity and defilement of nanoparticles in soil and define ecologically suitable dosages. In order to open up this new sector for sustainable agriculture, future research must concentrate on providing complete information in such uncharted territories.

Abbreviations ^{210}Po: Polonium-210; ^{232}Th: Thorium-232; ^{238}U: Uranium-238; *Ag*: Silver; Al_2O_3: Aluminum oxide; *As*: Arsenic; *Au*: Gold; *C*: Carbon; *Cd*: Cadmium; CeO_2: Cerium dioxide; *Cu*: Copper; *CuO*: Copper oxide; *Fe*: Iron; Fe_3O_4: Ferrous ferric oxide; *Hg*: Mercury; *K*: Potassium; *Mn*: Manganese; Mn_2O_3: Manganese(iii) oxide; *Mo*: Molybdenum; *N*: Nitrogen; *NP/NPs*: Nanoparticle/nanoparticles; *Ni*: Nickle; *P*: Phosphorous; *Pb*: Lead; *Si*: Silicon; *SOM*: Soil organic matter; *Ti*: Titanium; TiO_2: Titanium dioxide; *Zn*: Zinc; *ZnO*: Zinc oxide

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Data Availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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