NANOPARTICLES UPTAKE, UTILIZATION AND PHYTOTOXICITY IN PLANTS

Abstract

The applications of nanoparticles in agriculture are rapidly increasing owing to the unique characteristics and advantages of the nanoparticles. It is considered widely because of its efficiency in reducing the load of chemicals used in agriculture. However, regardless of all the advantages, they still threaten the health of living organisms and the environment. Consequently, collecting additional data and acquiring a deeper understanding of nanoparticles' absorption, translocation, and toxicity in plants is crucial. But the mechanism behind the uptake, translocation and phytotoxicity mechanism is still unclear. This chapter explores the absorption of nanoparticles through leaves and roots, factors influencing the uptake mechanism, translocation pathways, and phytotoxicity.

Keywords: Nanoparticles, phytotoxicity, translocation, uptake

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I. INTRODUCTION

The demand for food has increased significantly as the world's population has grown. Reduced agricultural area, water shortages, rising temperatures, and other climate-related factors are predicted to lead to lower crop yields soon [55]. Therefore, agricultural sectors must adopt and implement new advances, such as new technology and continual innovation. As a result, scientists have turned to nanotechnology to improve crop yields and product quality [61]. Nanoparticles range in size from 1 nm to 100 nm and may come in different shapes depending on their composition, origin and the qualities required for their intended use [65]. This approach provides a unique method for producing particles with desirable properties such as large surface area, small size, high reactivity, optical features, etc., previously impossible to achieve with bulk materials [43]. Agrochemicals and other macromolecules essential to plant development may be delivered to specific sites and released slowly with the help of nanoparticles, leading to more effective use and less environmental damage [15]. These nanoparticles, however, may hinder plant development and even induce phytotoxicity. It is crucial to comprehend the absorption process, the translocation of nanoparticles, and the phytotoxic consequences of these nanoparticles in particular [37]. It is thought that plants can take up and translocate nanoparticles, albeit this relies on several parameters like the nanoparticles surface charge, size, concentration, and so on. The stomata, cuticle, root hairs, and lesions on a plant are all possible entry points for nanoparticles [62]. It's vital to remember that nanoparticles undergo chemical changes as they enter the soil, the plants, and the bodies of living things. Their absorption, translocation, and toxicity are all controlled by environmental factors, such as their oxidation state, which may undergo various alterations. Nanoparticles, even those that seem stable at first glance, may undergo transformations that might turn their advantageous features into drawbacks [31]. To create the best nanoparticles for agricultural usage, it is essential to comprehend how plants take up and transport these particles [59]. Through a greater understanding of the mechanism underlying their action and bioaccumulation in plants, it is possible to elucidate the safety of nanoparticles and provide guidelines for the safe use of nanoparticles in agriculture [25]. Numerous studies have been conducted on plant-NP interactions, but the data on the uptake, translocation, and transformation of NPs and their effect on crops is scant and dispersed; thus, it will require some quick, creative reasoning to systematically convey the significance of NPs in agriculture. This review will shed light on how plants uptake and translocate nanoparticles and the toxic effect caused by them.

II. UPTAKE OF NANOPARTICLES IN PLANTS

Nanoparticles uptake in plants generally occurs in three steps: absorption, transformation of nanoparticles through leaf, stem or root surface, and ultimately taken up through stomata, cuticle and epidermis. From there, they transfer and transform through the xylem and phloem within the plant. The mode of application of nanoparticles to plants is through seed treatment, trunk feeding, foliar and root application [50]. However, root and leaf exposure is the most predominant and easy-to-use method. The stability, chemical composition, concentration, and size of the nanoparticles, among other factors, influence the absorption and translocation of nanoparticles in plants [31].

III. FOLIAR UPTAKE OF NANOPARTICLES IN PLANTS

When nanoparticles are sprayed onto a leaf, the plant may absorb them via the stomata or the cuticle, depending on which is more permeable. The waxy cuticle on the leaf epidermis protects the leaf from water loss and serves as a key natural barrier against nanoparticle penetration [40]. Plants store NPs mostly in vacuoles and the cell wall, but the xylem and phloem transport them both upward and downward to other regions of the plant. The cuticular route is further subdivided into two sub-pathways based on the solutes they transport. Hydrophilic uptake occurs through polar aqueous pores with an estimated effective size range of 0.6 and 4.8 nm [12]. Lipophilic uptake occurs through diffusion and penetration of nonpolar solutes. [22] demonstrated via high-resolution confocal fluorescence microscopy that carbon particles smaller than 2 nm can infiltrate cotton leaves via the cuticular route. Due to the small size of the pore channels in the cuticle, the epidermis of plants can only absorb a limited volume of nanoparticles. Nanoparticles may accumulate in the epidermis and vascular tissue after being applied to the leaf surface. Several investigations have identified nanoparticle translocation to various plant tissues [42].

Hydrophilic chemicals may also be absorbed through the stomatal system, shown in investigations to operate independently of the cuticular pathway. The morphological pore diameters of stomata found on the leaf surfaces of terrestrial and certain aquatic plants are 25 μm in length and 3-10 μm in breadth [59]. Stomata vary in size and density throughout plant families. Due to the stomata's unique geometric structure and physiological function, the stomatal aperture's true size exclusion limit (SEL) for nanoparticle diffusion is unknown [18]. [12] found that NPs can cross a pore if their particle size is 40 nm or less. This data provides more evidence that stomatal particle transport is size-dependent. According to the research conducted by [61], watermelons absorb metal oxide NPs between 24-47 nm in size via their stomata. They enter through the stomata and travel to the stems and roots via the phloem. Wounds are another direct entrance route for NPs into plants, the cuticle and the leaf. Some investigations have found that plants absorb NPs via wounds, as [23] described. The hydathodes in plants are another possible entryway for NPs. Angiosperm plants use guttation, facilitated by tiny pores called hydathodes, to eliminate excess water. The NP absorption and excretion throughout the hydathodes were described by [20]. [67] found insoluble nano 141-CeO_2 at the hydathodes located in the leaf tips and serrations of cucumber. [44] further demonstrated that nano-SiO_2 collected around the leaf tips and was expelled as salt. Atmospheric abiotic variables such as light, humidity, and temperature; qualities of NPs such as shape, size, and charge; plant physiological traits all have a role in the penetration, transfer, and accumulation of NPs [42].

IV. FACTORS AFFECTING THE UPTAKE OF NANOPARTICLES THROUGH LEAVES

Uptake of nanoparticles depends on various factors like size, chemical composition, shape, surface charge, environment and plant species etc. The properties of nanoparticles affect their absorption behaviour in plant leaves.

1. **Effect of Size and Chemical Composition:** Researchers have investigated the relationship between nanoparticle size and metal absorption. Due to the size exclusion limit of NPs in the blade absorption pathway [29], particle size has been regarded as one of the most critical factors in the study of nanoparticle absorption. According to the

research findings, metal-based nanoparticles with less than 50 nm diameter can enter leaves through the stomatal channel [18]. The capacity of leaves to absorb nanoparticles reduced as particle size increased. Foliar absorption of nanoparticles has been the subject of several investigations. For instance, [70] sprayed wheat leaves with ZnO nanoparticles tagged with fluorescein isothiocyanate (FITC). Confocal microscopy revealed that ZnO nanoparticles transported mostly through the stomata channel into the chloroplasts of wheat leaves. In addition, they studied how stomatal opening and closure affected ZnO NP uptake. Observational evidence showed that zinc levels in wheat leaf cells dropped by 33.2% in chloroplasts and 8.3% in cytoplasms when the stomatal diameter shrank. [4] employed gold nanoparticles modified with coatings of varying diameters (3, 10, and 50 nm) to affect wheat leaves. Wheat (*Triticum aestivum* cv. *cumberland*) leaves were discovered to absorb the coated gold nanoparticles of all sizes [13] .In a recent study, rice leaves can assimilate and distribute chitosan-made silicon nanoparticles with an average size of 166 nm [24].

2. **Influence of Form and Surface Charge:** Their shape and electrical charge also influence nanoparticles' ability to penetrate plant mesophyll tissue. The absorption of nanoparticles (NP) depends on their surface area and how they come into contact with the plant surface, both of which are affected by the interfacial properties of the nanoparticles themselves [51]. [67] found that when spherical gold nanoparticles were compared to rod-shaped nanoparticles of the same dimension, the latter was more difficult for Arabidopsis leaves to absorb and internalize. Leaves of plants may take in either positively or negatively charged nanoparticles.

3. **Effect of Plant Species:** The type of plant also plays a major role in how much nanoparticles are absorbed by the leaves [18]. Nanoparticle uptake is proportional to leaf pore size, density, and dispersion. For instance, the stomata of monocotyledonous plants are more orderly and uniform in shape than those of dicotyledonous plants. The rate of nanoparticle absorption in plant leaves is also influenced by the development stage and life cycle. Few plant species have stomata in their upper epidermis, whereas the overwhelming majority only have them in their lower epidermis [62]. When leaves had stomata on both surfaces, the number of stomata on the bottom epidermis of dicotyledon plants was nearly 1.4 times greater than that on the top epidermis. The number of stomata on both surfaces of monocotyledon plants was identical. [46] demonstrated that dicotyledonous pumpkins absorb CeO_2 nanoparticles more efficiently than monocotyledonous wheat. Tomato had a higher Ce NP absorption rate than festuca [28]. Abiotic factors, such as humidity, temperature, and light, also influence the rate of NP absorption [14].

V. ROOT UPTAKE OF NANOPARTICLES IN PLANTS

The roots of plants absorb soil nanoparticles and transport them throughout the plant. Nanoparticles make initial contact with the plant through adsorption on the root surface. Positively charged nanoparticles tend to accumulate in the root. They are readily absorbed on the root surface because root filaments may exude negatively charged chemical compounds such as mucus and organic acids [68]. Nanoparticles may be able to penetrate the root column if they encounter a novel adsorption interface, which may be formed as lateral roots develop [39]. The root epidermis is similar to the leaf surface in composition and function. However,

the major and secondary plant root epidermis is not entirely grown, nor is the epidermis on the surface of the root hairs.

Direct contact with the root epidermis and penetration occurs when nanoparticles are introduced here [41]. Semipermeable lipid membranes separate the epidermal cells of the root cell wall. Large particles may be blocked from entering the root system by the microscopic holes in the root cell wall [40]. A root lacking an exodermis is more susceptible to nanoparticle penetration of its xylem. Forlarge-diameter nanoparticles to enter the epidermis, specific nanoparticles must disrupt the plasma membrane and cause the formation of new pores in the epidermal cell wall. There are numerous mechanisms for the absorption of nanoparticles by plant cells upon their introduction to plant tissue. These include the ion route, endocytosis, protein binding to cell membranes, and direct physical injury. Studies have shown that the hydrophilic channel is the primary route by which plant roots take up nanoparticles and penetrate into cells.

Nonetheless, the tiny pore size means nanoparticle entrance into cells through this route is very restricted [31]. Endocytosis is also crucial for the uptake of NPs by plant cells. NPs are taken within plant cells through plasma membrane invagination. Endocytosis has been proven to be a means by which plant protoplasts may take up particles smaller than 1 μm. As this process does not discriminate based on particle size [32], nanoparticles ingested in this way are nonselective. According to [30], root cells of *Catharanthus roseus* are theorized to absorb carbon-based nanoparticles and carbon nanotubes utilizing endocytosis. When nanoparticles attach to transport proteins on the outer epidermis of a plant, the plant can absorb the particles.

VI. FACTORS INFLUENCING NANOPARTICLE ABSORPTION THROUGH ROOTS

The following are some of the factors that influence the uptake of nanoparticles in plants.

1. **Effect of mass and chemical constituents:** The main factor influencing how well nanoparticles are absorbed by plant roots is assumed to be their size. There has been evidence of nanoparticle absorption by plant roots in the past; for example, CeO_2 nanoparticles (8 ± 1 nm) [21] and gold nanoparticles (3.5 nm) [69] in the roots of maize and *Vicia faba* L., respectively. Additionally, several studies have shown a correlation between NP size and wheat root uptake. For instance, the roots of wheat plants may absorb TiO_2 nanoparticles ranging in size from 36 to 140 nm. As particle size increases, the total amount of absorption declines. However, TiO_2 NPs with a size greater than 140 nm are not extracted [27]. Most researchers concur that it is difficult for plants to absorb metal-based nanoparticles through their roots if the particle size exceeds 100 nm [5].

2. **Effect of surface charge:** NP assimilation by plants depends on both its size and surface charge [52]. For plant roots to absorb nanoparticles, their surface charge characteristics must be compatible with the negative charge of root cell walls. In contrast to the effect of electric charge on nanoparticle absorption in plant foliage, this effect differs slightly in plant roots [48]. Electrostatic interaction between the negatively charged cell wall and the positively charged nanoparticle results in the accumulation of positively charged nanoparticles on the root surface [7]. [38] created nanoparticles with variable particle

diameters (20-100 nm) and surface charges by reversible addition chain transfer polymerization. Both uncharged and negatively charged nanoparticles (22 nm) were conveyed into the xylem by root cells of *Arabidopsis thaliana*, as revealed by confocal microscopy. The positively charged nanoparticles, on the other hand, cannot reach the root tissue of Arabidopsis and instead congregate at the root epidermis.

VII. LEAF-MEDIATED TRANSLOCATIONS OF NANOPARTICLES IN PLANTS

The epidermis is the first barrier since the NPs have to penetrate on their way to the phloem after penetrating the cuticle. The mesophyll cells under the epidermis create a cell wall continuity (apoplast) and cytoplasmic continuity (symplast) connected by plasmodesmata. Through symplastic or apoplastic routes, NPs go from the mesophyll to the bundle sheath cells and from there to the companion cells and sieve tubes of the phloem [42]. On their way to the phloem, NPs in apoplastic pathways must cross fewer membrane barriers than those in symplastic pathways, which must traverse a more significant number of plasmodesmata. It is difficult for researchers to determine whether NPs move through apoplastic or symplastic pathways in plants due to an inability to visualize NPs in plant tissues at a high enough resolution to determine these pathways and a lack of a sufficient method for sample preparation that can avoid artefacts [45]. Apoplast is often used for transferring NPs between 50 and 200 nm, whereas symplast is used for transferring NPs between 10 and 50 nm [4].

Due to the small pore size of plasmodesmata, typically between 2 and 20 nm, the symplastic route is more preventative than the apoplastic pathway for NP movement. Apoplastic transport plays an essential role in either facilitating or impeding phloem loading; therefore, strategies should be developed to maximize their potential for this transport route during fabrication and application [8]. Several studies have shown that the foliar spraying of NPs results in uptake by other plant tissues, including stems, flowers, seeds, roots, etc. The xylem and the phloem are involved in the distribution of NPs throughout the plant. Phloem transports carbohydrates synthesized during photosynthesis to where required, such as apical meristems, fruits, and developing leaves that cannot photosynthesize adequately or downward to the roots [26]. Water and nutrients are transported from the roots to the shoot via the xylem.

The parameters that influence phloem accumulation and, thus, the translocation of NPs to the partner cells and sieve tube are not presently described in detail. Although symplast diffusion is prevalent in plants, not all plant species have apoplastic loading of the phloem [36]. When applied to leaves, NPs go down the xylem to the phloem and are transported through the sieve tubes. Because of its high solute potential, the phloem containing the NPs has a lower water potential than the xylem cells that surround it. The transport of water from the xylem to the phloem is facilitated by osmosis. The water pressure in the phloem generates a two-way flow that transports particulates upward to the leaves, flowers, fruits, and seeds or downward to the roots. For phloem drainage, passive or active transport may be employed. After unloading, the phloem has a higher water potential than the xylem and a lower concentration of particles (solute potential). Therefore, the phloem transports water to the xylem [11].

Since photosynthates have been shown to undergo osmotic exchange [11], this suggests that NP exchange may also occur between two (or more) compounds. Following

foliar treatment, phloem sieve tubes and xylem vessels in French beans accumulated carbon nanoparticles [19]. The research mentioned above concludes that their transmission causes the translocation of NPs in plant tissues through phloem-to-xylem in the shoots and through the xylem into rhizosphere soil. Understanding the mechanism of various NP transport strategies is crucial for optimizing their delivery to target plant tissues. Transport of big particles is more challenging in xylem vessels due to their smaller pore size, but particles up to 0.405 μm in size may flow readily via phloem sieve tubes. Only particles less than 100 nm in size may go via the xylem. Therefore, their size and aggregation impeded NP translocation via phloem and xylem [8].

VIII. ROOT-MEDIATED TRANSLOCATION OF NANOPARTICLES IN PLANTS

NP transport in plants involves both an apoplastic and a symplastic pathway [4]. The Casparian strip, formed between the radial and transverse endodermal walls, prevents NPs and other macromolecules from accessing the circulatory system after traversing the epidermis and cortex via the apoplastic route. Since the Casparian strip is either not present at the lateral root junction or is incompletely formed in the root tip region, NPs may circumvent the Casparian strip and gain access to the vascular system in these regions [47]. NPs enter the cytoplasm via the PM or are conveyed to neighbouring cells via plasmodesmata via the symplastic pathway. Numerous studies support this assertion, including [17] and [66].

Regarding NP translocation, both the apoplast and symplast transport routes play significant roles. However, carrier proteins, aquaporins, and the endocytosis process make the symplastic pathway the most common route for NP transfer. Hydrophobic and hydrophilic TiO$_2$ NPs were applied to carrots in a hydroponics experiment. The research found that the size of the NPs, rather than their surface coating, controlled their absorption and translocation. Translocation of the tiny NPs is facilitated by their ability to penetrate the root via the root surface [63]. The Zn absorption of *Phaseolus vulgaris* after 48 h of treatment with ZnO NPs (40 and 300 nm) was studied. Where 40 nm ZnO NPs were more readily absorbed by roots than 300 nm ZnO NPs, the concentration and uptake rate gradient for the transport of Zn from roots to branches via the xylem decreased [10]. The process by which NPs are taken up by plant roots remains inadequately understood despite the profusion of knowledge regarding mineral element transport.

IX. PHYTOTOXICITY CAUSED BY NANOPARTICLES

Although NPs have several advantages, their toxicity to plants limits their use in farming. Plants are harmed in several ways by the toxicity of nanoparticles. Among these effects are the stimulation of oxidative stress, aggregation of NPs, release of toxic metal ions, damage to proteins and DNA, and inhibition of normal metabolic processes in cells [16]. Before being recommended for use in agriculture, NPs should undergo a comprehensive evaluation for their potential as agrochemicals [64].

1. **Toxic effect of Nanoparticles on Plant Growth:** Several studies have demonstrated that foliar applied NPs accumulate on leaves, resulting in the closure of pores or foliar burns, which reduces gas exchange, photosynthesis, and nutrient absorption. The toxicity of NPs to plants is very sensitive to their concentration and their application. For instance, Zn and Cu NPs harm plants when treated in quantities over a threshold value, resulting in stunted development and leaf chlorosis [64]. Root and shoot development and photosynthetic

efficiency are stunted in *H. sativum* due to the toxicity of CuO NP [41]. When nanoparticles endure internal chemical changes (redox and valence transformation), they disrupt cell structure, block ducts, cell wall apertures, and stomata, impeding a plant's ability to absorb and transport nutrients [53]. It is one of several improvised methods for reducing NPs' toxicity that the surface coating strategy is very effective at reducing the unbound hazardous ions produced by NPs. Coating ZnO NPs with Fe, for example, reduces their phytotoxicity because the Fe prevents the NPs from emitting $Zn2^+$ and the improved NPs influence pigment content or germination. Polymer encapsulation or surface modification of nanoparticles may also reduce their phytotoxicity [49]. Understanding the harmful effect of nanoparticles requires careful consideration of their impact. *Allium cepa* roots were treated with silver nanoparticles of size 10 nm at 25, 50, 75, and 100 μM with various surface coatings. When administered at greater doses, all the AgNPs evaluated generated oxidative stress and showed signs of toxicity. A substantial decrease in root development and oxidative damage were observed for AgNPs-CTAB, which was associated with the most significant toxicity [9].

2. **Plant Genotoxicity and Oxidative Stress Damage brought on by Nanoparticles:** [34] state that increased plant reactive oxygen species (ROS) production due to nanoparticle interaction with plants results in oxidative damage and genetic toxicity. As all aerobic creatures respond to environmental changes, plant cells also produce ROS. When ROS levels outpace defensive mechanisms, damage to nucleic acids, proteins, and lipids in cell membranes is unabated, resulting in "oxidative stress" in the damaged cells [62]. Reactive oxygen species (ROS) negatively affect cells, although antioxidant enzymes and substances found in plants may be able to mitigate this. Plants have a defensive mechanism against the toxicity of active oxygen radicals in cells and subcellular systems, this is because of the low molecular weight antioxidants and antioxidant enzymes [2]. Therefore, evaluating antioxidant enzyme activity and reactive oxygen species (ROS) levels is the main focus of research into the oxidative damage caused by nanoparticles. Numerous studies and analyses have revealed excessive nanoparticle accumulation in plants and an abundance of reactive oxygen species (ROS) that stimulate the antioxidant system, especially when nanoparticles are present in high quantities [53]. As the concentration of plastic NPs increased, the activity of several common antioxidant enzymes in rice roots increased, suggesting that the plant may mount a defence and eliminate the excessive accumulation of ROS [69]. Also, the transformation and release of harmful metal ions by metal-based nanoparticles in plants is detrimental to plant health, as it leads to the breakdown of DNA and proteins and a reduction in cell metabolism [35].

Nanoparticles are genotoxic and can induce ROS generation and hormonal alterations in plants. Plant cell division may be disrupted when nanoparticles interact with nuclei and lipids, cause genotoxicity. For instance, Ag NPs internalized in wheat root tips interrupted normal cell division, hindered DNA synthesis, and resulted in chromosomal abnormalities, according to research by [1]. Additionally, onion cells exposed to PS NPs showed chromosomal aberrations and nuclear abnormalities, which caused the breakdown of genomic integrity and demonstrated the genotoxicity of PS NPs [33]. Researchers have found remedies to the toxicity of nanoparticles, such as coatings that may effectively minimize the hazardous compounds generated by nanoparticles. For instance, the release of zinc ions may be greatly reduced by covering zinc oxide nanoparticles with iron. Fe-coated zinc oxide nanoparticles in soil have no impact on seed germination or plant pigment synthesis [49]. To reduce their toxicity, polymer nanoparticles may potentially

benefit from encapsulation or surface modification [42]. Analyzing the toxicity of different nanoparticles as agricultural pesticides might help establish the proper concentration of nanoparticles for plant growth. Because they are nontoxic, biocompatible, and degradable compound nanoparticles, natural polymer nanoparticles can largely avoid the adverse effects of metal-based, silicon-based, and organic-based nanoparticles on plants and the environment [3]. Chitosan is the only positively-charged polysaccharide known in nature, and because of its antibacterial and antiviral properties, it has been called a nanoparticle substance. Chitosan nanoparticles with positive charges have a stronger affinity for plant cell membranes and are more sensitive to outside stimuli. It has been demonstrated that applying chitosan-based nanoparticles to seeds and seedlings as a plant growth promoter improves the plants' capacity to absorb nutrients, boosts the amount of chlorophyll in the plants, and quickens the pace of photosynthesis. Plants were treated with chitosan nanoparticles ranging in size from 420 to 970 nanometers. The findings demonstrated an increase in chlorophyll content of 61%, 81%, and 61% in plants, and an increase in the photosynthetic rate of 29%, 59%, and 72%, respectively [56]. Chitosan nanoparticles applied to wheat and barley have increased crop yields [6].

3. **Effect of nanoparticles on plant hormones:** Plants' natural hormone production is affected by nanoparticles [68]. NPs impact the expression of genes in plants involved in hormone synthesis and signal transmission. Additionally, studies are being conducted to determine how nanoparticles impact the hormones that are naturally present in plants [57]. Iron oxide nanoparticles at a concentration of 100 mg/L caused a rise in hormone levels and a drop in the production of Bt-transgenic cotton. The hormone levels in Bt-transgenic cotton roots decreased in contrast [55].

X. CONCLUSION

Nanoparticle uptake, transport, and toxicity studies in plants are discussed here. NPs are crucial in increasing agricultural production and productivity and developing plant tolerance to a wide range of stresses. However, studies on how NPs are taken up and moved and their effects on farming are only beginning to emerge. There hasn't been a comprehensive look at how NPs of varying sizes, surface charges, and elemental compositions are absorbed, transformed, and transported by plants. More research is required to ascertain how NPs are transported through these systems because morphological and physiological aspects of plants, such as sap flow rate in xylem, pore size of the membrane in plants and phloem, and connection between xylem and phloem, differ between plants and even within the same plant. The mechanisms of NPs uptake, translocation, and transformation in plants, such as the mechanism of NPs passing through the cuticle layer of roots or leaves, the SEL for NPs to cross the various barriers of plant cells, the sites for NPs accumulation and transformation within plants, whether or not special enzymes are needed for NPs translocation and transformation, analysis of apoplastic and symplastic pathways, and the energy source of xylem and phloem needs more research to understand better. Soil and field tests should be conducted to collect data relevant to the environment on the interaction between plants and NPs. There has to be more research done on how NPs interact with the environment, how they could affect human health, and how they might cause plant toxicity before they can be sold commercially. Research priorities should centre on determining the optimal concentration of NPs for plant development via the study of the toxicity of various NPs utilized in agriculture. Research on biosynthesized NP-based fertilizers and nano-

biofertilizers is warranted as a promising new avenue for increasing crop yields. Future research must be expanded to learn about the uncharted regions so that this new approach to sustainable agriculture may be introduced.

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