Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook

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In the current scenario, it is an urgent requirement to satisfy the nutritional demands of the rapidly growing global population. Using conventional farming, nearly one third of crops get damaged, mainly due to pest infestation, microbial attacks, natural disasters, poor soil quality, and lesser nutrient availability. More innovative technologies are immediately required to overcome these issues. In this regard, nanotechnology has contributed to the agrotechnological revolution that has imminent potential to reform the resilient agricultural system while promising food security. Therefore, nanoparticles are becoming a new-age material to transform modern agricultural practices. The variety of nanoparticle-based formulations, including nano-sized pesticides, herbicides, fungicides, fertilizers, and sensors, have been widely investigated for plant health management and soil improvement. In-depth understanding of plant and nanomaterial interactions opens new avenues toward improving crop practices through increased properties such as disease resistance, crop yield, and nutrient utilization. In this review, we highlight the critical points to address current nanotechnology-based agricultural research that could benefit productivity and food security in future.

Keywords: food, agriculture, nanotechnology, nano-pesticides, biosynthesized toxicity, bioavailability, sustainability, soil

INTRODUCTION

Agriculture acts as the primary pillar of the developing economy and provides food for a better life. In the current scenario, the field of agriculture has been facing a wide range of challenges, including unpredictable climate change, contamination of soil with various harmful environmental pollutants such as fertilizers and pesticides, and majorly elevating food demands with a growing global population (Pouratashi and Iravani, 2012). A recent report by the United Nations projected that the global population would become 8.5 billion by 2030 and approximately 9 billion by 2050 (https://population.un.org/wpp/Publications/Files/WPP2019). Therefore, to meet the demands of the relentlessly growing population, there is an urgent need to increase food production more than 50%. On the contrary, industrialization leads to depletion of natural resources on which the population's livelihood depends, such as oceans, forests, and ecological biodiversity, at an alarming rate (Kang et al., 2009). Thus, it advocates the need for increased crop production and better food security. Ecological biodiversity plays an essential role in maintaining the delicate balance of the environment and food production as it strengthens agricultural resilience toward the environmental stress that potentially leads to crop failure. More specifically, the biodiversity...
for food and agriculture comprises livestock, crops, forestry, and aquaculture systems by which human beings are sustained. Oceans and forests are home to numerous animal and plant species that majorly withstand world population for food, fodder, fuel, and fiber. Thus, any issues that could cause ecological disequilibrium significantly affect food security (http://www.fao.org/3/CA3129EN/CA3129EN.pdf; https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/; Rice and Garcia, 2011). In order to deal with these pertinent issues, newer techniques and strategies are continuously evolving. Given this, one such step taken is the introduction of nanomaterial (NM) based products for revolutionizing modern agriculture practices. These materials bear high reactivity due to their large surface area–to-volume ratio and novel physicochemical properties that provide the clear advantage of required modification according to elevating demand.

Previously, nanotechnology has been utilized in multiple fields, including chemistry, pharmaceutical science, diagnosis, and therapeutics, to name a few (Leso et al., 2019; Stefan and Monchaud, 2019; Li W. Q. et al., 2020). Nanoparticles (NPs), at the forefront of nanotechnology, are incorporated into a variety of consumer products owing to their tremendous potential as compared to their bulk counterparts (jeevenandam et al., 2018). Therefore, the unique and emerging properties of these new-age materials have drawn unequivocal attention in the food and agriculture sector.

Modern agriculture is transforming into precision agriculture with the help of these new-age materials that are helping to gain maximum output from the available resources. Various types of other NMs, such as nanoclays, nanotubes, and nanowires, possess unique surface chemistry, electrical, and optical properties (Yaqoob et al., 2020) that provide them with better sensitivity, improved detection limits, and rapid response times (Kumbhakar et al., 2014). Fertilizers are necessary to enhance crop production, but at the other end, they decrease soil fertility by disturbing the soil mineral balance (Solanki et al., 2015). Generally, pesticides, fertilizers, and antibiotics are sprayed, which can be run off efficiently. Furthermore, the cost of production of these pesticides and fertilizers is very high, which needs to be controlled. The application of NMs in agriculture aims to reduce nutrient losses to increase yields, reduce the amounts of products for plant protection (Usman et al., 2020), and minimize the cost of production to maximize output. In the current review, we suggest and provide the facts that NMs deliver a better solution to improve agriculture and food systems. However, we also highlight the fact that it is vital to test the extent of toxicity of NM-based products before implementing them in the market. Nanotechnology-based products, such as smart agrochemical delivery systems using NMs as a carrier of active ingredients, are being continuously developed. The waste products of agriculture, such as soy hulls and wheat straw, can be converted into advanced bionanocomposites having improved mechanical and physical properties to be utilized for industrial purposes. Some progress is still needed to gain the practical advantages of nanotechnology, such as better design of processes, risk assessment of nanopesticides and nanofertilizers, and regulations for commercialization of nanogrow products (Chen and Yada, 2011; de Oliveira et al., 2014; Amenta et al., 2015). Another challenging issue yet to be resolved includes farming systems to deal better with unpredictable climate variability, including new varieties of crops that can sustain drought, heat, and other environmental stress to convey the whole spectrum of modern farming practices worldwide (Elias et al., 2019). We strongly believe that a broad perspective of nanotechnology is essential to fulfilling the goal of helping foster global agriculture.

**NP INTERACTION WITH PLANTS**

The agricultural sector is benefiting from advancements in science and technology, which give us new ideas and solutions to combat severe problems. With the advent of nanotechnology, more efficient and fewer contaminant nanoformulations are continuously produced for sustainable agriculture (Fraceto et al., 2016). These new-age materials have the potential to alter the physioloogy of plants right after entering the complex plant–soil system that can be easily exploited to understand the aftereffects (Figure 1). Moreover, for controlled delivery of active compounds, critical knowledge of the interaction of these NMs with plants, either positive or negative, is required. Thus, they could provide novel avenues toward developing better nanomaterial-based products. It is also believed that the concentration of NMs in the natural environment is much lower than levels considered harmful. However, still, some gaps are left to be filled with comprehensive safety assessments (Batley et al., 2013).

**Systemic Approach for Selectivity of NMs: Physicochemical Property-Based Uptake and Interaction**

Several factors are responsible for the uptake and transformation of NPs: prominently, plant physiology, physicochemical properties of the NP itself, size, surface charge, shape, and potential interaction with plants (Pérez-de-Luque, 2017).

**Size-Dependent Uptake of NPs**

Size of the NPs must be considered as a significant parameter to study the uptake in plants as various barriers confined within the plants are in the range of micrometer (mm) to nanometer (nm) (Figure 1A). For instance, the epidermis foliar is made up of the cells that form a cuticle membrane. The epidermis consists of stomata containing two guard cells forming a pore of about 3–12 µm wide and 10–30 µm long during the opening for gaseous exchange. Therefore, NPs can make their way through the plants by virtue of these stomatal openings. Additionally, the permeation properties substantially differ for the cuticle layer on the epidermis and trichome of the stomata. The cuticle layer, on the other hand, presents in a more significant amount on the leaf epidermis with a size exclusion limit in the nm range (Wang P. et al., 2016; Wang X. et al., 2016; Figures 1B,C). It was described that NPs with a size range of 4–100 nm could cross the cuticle by disrupting the waxy layer (Larue et al., 2014), and fluorescently tagged NPs > 50 nm can accumulate in the epidermis underneath
the cuticle where stomata are absent (Nadiminti et al., 2013). The polymeric NPs of 43 nm diameter are able to penetrate the leaves of *Vicia faba* solely through the stomata, whereas particles of 1 µm did not cross at all (Eichert et al., 2008). NPs usually get deposited on the cell wall of the substomatal cavity when entering through the stomata. The likely penetration of small-size NPs, for instance, 20 nm Fe$_3$O$_4$ NPs, were observed through TEM studies in the *Nicotiana benthamiana* plant (Cai et al., 2020; Figures 1B, C).

The principal size exclusion limit was mainly imposed (Palocci et al., 2017), notably, by these plant cell walls that are usually in the size range of 3.5–20 nm and more often around 5 nm (Carpita et al., 1979; Tepfer and Taylor, 1981). Thus, NPs smaller than 5 nm can traverse the cell wall of intact cells efficiently. In one study, SWCNT was able to form an endocytosis-like structure in the intact cell wall of the *Arabidopsis thaliana* plant (Shen et al., 2010). It is suggested that NPs within a size range limit according to the cell wall can traverse through it. For example, quantum dots (QDs) fall under the size range of plant cell wall pores (<10 nm) that can be easily exploited to make their entry through the plants (Wu et al., 2017a). Li et al. observed the presence of AgNPs of size 24.8–38.6 nm within lettuce leaves when applied through the foliar route. They also demonstrated the in planta transformation of AgNO$_3$ applied with AgNPs that also explains the biotransformation phenomenon (Li W. Q. et al., 2020).

The interaction of NPs with the cell wall creates large-size pores that further facilitate the entry of NPs (Carlson et al., 2008). Further, there are results on the accumulation of larger sized NPs in the cell wall and subsequently in the cytoplasm, but a discrepancy between the claimed pore size of the cell wall
The presence of positively charged NPs at root surfaces. However, negatively charged cerium oxide NPs is found with dicot plants, such as tomato and lettuce, with a larger root surface area. However, better root-to-shoot translocation is observed with neutral and negatively charged NPs (Spigelman-Sun et al., 2019). This suggests that anatomical and physiological differences in plants result in differential uptake patterns of NMs, which is also evidenced by observations that diverse crops belonging to different species show a varied pattern of accumulation and absorption of distinct classes (e.g., TiO$_2$, carbon-coated, Au) of NMs (Cifuentes et al., 2010; Larue et al., 2012c; Figures 1B, 2A).

The dicots, in comparison to monocot plants, show higher uptake of NPs due to more permeability in the cuticles. This is proven in the case of lipid-based liquid crystalline nanostructures, which are utilized as a delivery vehicle (Nadiminti et al., 2013). This difference is attributed to the different architecture of the cell wall in monocots and dicots. In monocots, the pectin polymer is less tightly bound to the cellulose (Carpita and Gibeaut, 1993). Another significant anatomical difference is in the leaf architecture, such as the presence of dumbbell-shaped stomata in monocot and kidney-shaped stomata in dicot plants, resulting in variable degrees of uptake and translocation efficiencies of NPs (Figures 1B, 2A).

Additionally, the leaves of monocots have parallel veins that are most resistant to tearing and, therefore, have high strength (Avellan et al., 2017; Hu et al., 2020). The ability of plants to take up these NMs also depends upon the mode of their application as roots absorb nutrients from the soil, leaves are meant for the exchange of gas, and cuticles hamper the penetration of any substance freely (Schwab et al., 2016). However, drought-resistant plants develop tighter cell walls, cuticles, Caspian strips, and other barriers that are helpful to minimize water loss during scarce weather conditions (Riederer and Schreiber, 2001). Some of the essential factors of the soil, such as organic matter and humic acid, make NMs more stable, which, conversely, enhances their bioavailability (Navarro et al., 2012). The presence of bacteria and mycorrhizal fungi living in association with plants also affects the plant uptake of NPs (Feng et al., 2013). The transport of CuO NPs from root to shoot and its reverse transport from shoots back to roots takes place via xylem and phloem, respectively (Wang Z. et al., 2012).

NPs can also utilize a clathrin-independent endocytic pathway for gaining entry into the plant. Poly (lactic-co-glycolic) acid (PLGA) NPs follow this pathway as treatment of inhibitors
FIGURE 2 | (A) NP-based nano pesticide and fertilizer delivery to the plants and release in the environment. (1) Selection of nano-shells for active component encapsulation. (2) Application in the field includes direct delivery and carrier-mediated delivery. (3) The steady release of the active component of the nano fertilizers in the environment for sustainable release. (B) Various microscopic and spectroscopic techniques employed for the detection of nanoparticles.

of the clathrin-dependent pathway do not hamper its uptake into the grapevine (V. vinifera) protoplast. The size and surface characteristics of the NPs play essential roles in determining the uptake inside the plants as evidenced by a study conducted on foliar uptake of AuNPs on wheat that explains efficient translocation of smaller size NPs with a surface coating of PVP-AuNPs rather than citrate-AuNPs (Avellan et al., 2019). Another study shows no uptake of SWCNT by cucumber seedlings, but in the form of nanosheets, they were able to interact with the external surface of the roots (Cañas et al., 2008). It shows that the uptake of NMs is highly dependent on the type of delivery method used. In this context, Su et al. investigated the fate and mobility of surface-modified AgNP delivery to trees by employing various methods, including direct tree injection and petiole feeding in Mexican lime citrus trees (Su et al., 2020). Further explanation of uptake and transport in conjunction with the fate and transformation of NMs is comprehensively reviewed by different groups (Lv et al., 2019; Su et al., 2019).

Methods to Study Uptake, Quantification, and Translocation of NPs
Potential techniques must be developed to track the interaction taking place between plants and NMs; moreover, more vital information is needed to quantify the uptake and translocation of NPs inside plants and as released in the environment (Figure 2A). In this context, the assimilation and concentration of iron (Fe$_3$O$_4$) NPs in pumpkin (Cucurbita maxima) plants were quantified by employing a vibrating sample magnetometer to confirm the presence in roots and leaves (Zhu et al., 2008). Similarly, Fe$_3$O$_4$ NPs can also be measured and tracked in plant organs by exploiting its magnetic properties, such as temperature and magnetic field dependence of magnetization (Govea-Alcaide et al., 2016). The major problem with tracking and translocation of Fe$_3$O$_4$ NPs is associated with the inability to distinguish between intact Fe$_3$O$_4$ NPs and leached ions, which further can be solved by utilizing magnetic particle spectrometry in conjunction with
conventional atomic absorption spectroscopy (Ju et al., 2019; Figure 2B).

Also, the electron microscopy technique was used to track the translocation of C70 fullerene and MWCNT from roots to aerial parts (leaves) of rice (Oryza sativa); however, the authors did not quantify the amount of NPs taken up by the plants (Lin et al., 2009). In this regard, the uptake of MWCNTs in wheat and rapeseed plants was quantified through transmission electron microscopy (TEM) and the Raman spectroscopy technique (Larue et al., 2012b).

Critical imaging techniques, such as X-ray and computed tomography (CT), are beneficial to detect and localize various NMs in plants. Recently, to localize gold NPs in the roots of A. thaliana, a combination of techniques such as X-ray computed nanotomography (nano-CT), enhanced dark field, and hyperspectral (DF-HSI) imaging was used. The combined use of 2-D (DF-HSI) and 3-D (nano-CT) techniques provides better means to characterize and evaluate the NP–plant interaction at the cellular level (Avellan et al., 2017). Another non-invasive, highly sensitive method to visualize NPs through the combination of autoradiography, positron emission tomography (PET)/CT, TEM, and SEM was demonstrated in lettuce (Lactuca sativa) (Davis et al., 2017). In a pioneering study, the effect and interaction of TiO2 NPs with garlic (Allium sativum) was observed through spectroscopic techniques using time-resolved, laser-induced fluorescence and ultraviolet-visible spectra. The resulting increased chlorophyll content and enhanced photosynthetic activity in leaves of garlic plants were observed as compared to the control. The authors reported a decrease in the intensity ratio of red and far red chlorophyll fluorescence bands, suggesting a rise in photosynthetic activity and chlorophyll content (Bharti et al., 2018). Two-photon excitation microscopy as a novel strategy was employed for in vivo detection of MWCNTs, TiO2 and Cerium oxide NPs in wheat tissues (Wild and Jones, 2009). Other essential techniques, such as microscopy and spectroscopy, are highlighted in Figure 2B.

Although microscopy techniques provide a clear advantage in analyzing NPs in different samples, they have some main limitations, including sample preparation, a partial area of analysis, and limited 3-D imaging, which further requires alternative solutions. In view of this, inductively coupled plasma-mass spectroscopy (ICP-MS), in particular, single-particle ICP-MS (SP-ICP-MS) analysis, is a promising method for detection, characterization, and quantification of NMs (Mozhayeva and Engelhard, 2020). Similarly, SP-ICP-MS is utilized to quantify the uptake of CuO NPs in edible plants, lettuce, kale, and collard greens (Keller et al., 2018).

Mass spectrometry–based analytical techniques help distinguish between different chemical forms of NMs as they can readily be transformed once they enter the plant. One such approach utilized SP-ICP-MS and ESI tandem MS to confirm the fate of ZnO NPs inside the edible plant lettuce (Wojcieszek et al., 2019). The Au NPs were quantified by using ICP-MS in order to observe the uptake mode and accumulation in watermelon plants (Raliya et al., 2016). The significant advantage of these potential techniques lies in either their cumulative power or utilizing them in combination. The simultaneous uptake, retention, and distribution along with the plant were studied by Nath et al. for Ag, Cu, and ZnO NPs in A. thaliana using SP-ICP-MS, SEM, and EDS (Nath et al., 2018). Similarly, the combination of three orthogonal techniques, such as electron microscopy, SP-ICP-MS, and ICP-OES, is used to study the uptake and size distribution of TiO2 NPs in rice plant (Oryza sativa L.) tissues (Deng et al., 2017).

The Physiochemical Response of Plants Toward NPs

NPs for Plant Growth and Seed Germination

The uptake of NMs inside plants largely depends on the size, chemical composition, and functional groups present on their surface and the type of coating. The interaction and uptake of NMs lead to changes at the molecular level and affect the overall physiology of plants (Jin et al., 2017). The promising effect of multiwalled carbon nanotubes (MWCNTs) on the growth (55–64% increase) of tobacco cells involves a unique molecular mechanism. The majority of the activated genes involved are related to cell division (CycB), cell wall extension (NtLRX1), and tobacco aquaporin (NtPIP1) (Khodakovskaya et al., 2012). The ability of NMs to penetrate the hard coating of seeds and allow water importation is the deciding factor for increased growth and vigor. In addition to this, the seed priming technique with the help of nanotechnology is a promising strategy; before sowing, it further corroborates the potential of high-yield value crops (Acharya et al., 2020; Anand et al., 2020).

The application of MWCNTs affects the growth of some important crops, such as barley, soybeans, and corn. MWCNTs aggregate inside the endosperm of exposed seeds, which was confirmed by Raman spectroscopy and TEM imaging (Lahiani et al., 2013). NPs were transported to different parts of the plant and interacted with cellular machinery, thus promoting plant growth. NPs made of mesoporous silica (MSNs) can improve photosynthesis by interacting with chloroplasts, resulting in enhanced seed germination, increased total protein, and chlorophyll content. The highest concentration (2,000 mg/l) of MSNs did not induce stress conditions in any of the plants, which is indicative of its safer application as a smart delivery system (Sun et al., 2016). Silica plays an essential role in providing nutrition as its deficiency consequently makes plants weaker and highly susceptible to biotic and abiotic stress (Rafi et al., 1997). The application of silica also helps to ameliorate the effect of drought stress and increase biomass in stress-affected plants (Ahmad et al., 2007). Maize plants show better response toward the application of silica NPs (SiO2 NPs) prepared from rice husk and thoroughly characterized as compared to its bulk counterpart and control. Silica uptake was enhanced, and roots were elongated in the maize plants; this helps to withstand drought conditions. Root sectioning also reveals the direct uptake and accumulation of SiO2 NPs in the epidermis cells of maize (Suriyaprabha et al., 2012). The detailed impact of SiO2 NPs on agriculture has been extensively reviewed by Rastogi et al. (2019).

Another potential NP such as TiO2 also promotes the growth of plants as evidenced in canola (Brassica napus), which resulted...
in promoted seed germination as well as seed vigor. The highest effect was seen at a concentration range of 1,200–1,500 mg/l with increased plumele growth and large radicle as compared to the control (Mahmoodzadeh et al., 2013). The effect of any NP can be positive and negative, depending on its additive concentration and size. The smallest TiO₂ NPs accumulate more in plants as compared to larger particles (Larue et al., 2012a). Moreover, these NPs can also affect the miRNA levels to initiate the growth-promoting pathways in plants (Boykov et al., 2019).

The positive effect of Fe NPs on the Capiscum annuum plant at lower concentrations was found with increased plant growth by increasing chloroplast number and grana stacking. In contrast, when these NPs were applied at higher levels, they caused harm to the plant (Yuan et al., 2018). Other metal oxide NPs, such as ZnO and Cu, are observed to affect seed germination in Vigna mungo, i.e., black gram (Raja et al., 2019). The seed germination and growth-enhancing properties of less studied polyvinylpyrrolidone (PVP) protected platinum NPs in Pisum sativum (Rahman et al., 2020). Another critical and biocompatible NP, chitosan, exerted its effect on seed germination and growth by elevating the levels of indole-3-acetic acid (IAA) concentration in wheat or Triticum aestivum L. even at a shallow concentration (Li et al., 2019).

RECENT ADVANCES IN NPs FOR PLANT PROTECTION

The application of NPs (described in the previous sections) influence various important factors of the plant's growth and development that include photosynthesis, seedling vigor, and growth of roots and shoots. Plants are found everywhere; therefore, they have to bear extreme environmental conditions, such as drought, salt stress, high temperature, UV radiation, and salt stress. A number of different stress responses is shown by plants, such as alterations in molecular mechanisms, stress-responsive gene expression, and production of antioxidative enzymes that help to play a central role in scavenging the plants in harsh environmental conditions (Rejeb et al., 2014). Plants protect themselves from osmotic stress by producing various organic osmolytes, such as polyols and trehalose, and also different amino acids, such as proline and glycine. NPs provide an efficient way or, in other words, provide support to plants in alleviating this protection mechanism.

NPs Mitigate Abiotic Stress Response

In addition to helping plants grow, NPs also protect them from abiotic stress. Toxic metal binds to the surface of the NP owing to its large surface area and small size, thus reducing its availability. Abiotic stress includes drought, salinity, alkalinity, temperature fluctuations, and mineral and metal toxicity. NPs can mimic the activity of antioxidative enzymes in the form of nano-enzymes that can scavenge from oxidative stress (Sharifi et al., 2020). Photosynthesis is the vital metabolic process in plants and one of the highly susceptible methods; thus, by mitigating oxidative and osmotic stress, its normal functioning can be maintained. In the photosynthetic machinery, photosystem II (PS II), Rubisco, and ATP are the primary targets under stress conditions (e.g., nutrient deficiency, salinity, water, drought, and heat; Figure 3).

Th defense response in plants against abiotic stress was studied; for example, SiO₂ NPs improved plant transpiration rate, water use efficiency, total chlorophyll, and carbonic anhydride activity in the Cucurbita pepo plant in response to a defense mechanism against salt stress ( Siddiqui et al., 2014). Similarly, it was found that TiO₂ (anatase) changes the photoreduction activity and inhibits linolenic acid in the electron transport chain. It also decreased the rate of oxygen evolution of chloroplasts (Mingyu et al., 2008). In stress conditions, ROS are produced by the cell organelles, and this is the signature of abiotic stress. Plants are also equipped with the enzymatic machinery to deal with the oxidative stress imposed by the environment on them (Figure 3). However, plants face the consequences of such a situation when stress overcomes the defense system. NMs help in mitigating such stress by activating specific genes, accumulating osmolytes, and providing free nutrients and amino acids (Table 1).

CeNPs (CeO NPs)

Nanoceria has broad implications on plant health, both positive and negative, depending on the exposure concentration, coating, surface charge, plant species, and growth conditions (Milenković et al., 2019). Nanoceria is a family of CeO NPs with wide application as an antioxidant in the biomedical industry (Li and Shi, 2019). Although NPs can impose some severe effects on plants, as we look into the positive aspects of these NPs, it outweighs the negative impacts and can be exploited to provide health benefits to plants (Table 1). As we discuss earlier, the potential interaction at the nano–bio interface, these NPs could augment the tolerance against various abiotic stress of plants by regulating essential pathways (Saxena et al., 2016). For instance, abiotic stress leads to excessive ROS production that consequently decreases the photosynthetic performance of the plant and could cause biomolecule oxidation (Wakeel et al., 2020). Thus nano-Ce is well-suited to mitigate this effect owing to the unique redox potential based on the facile transition between Ce³⁺ and Ce⁴⁺ oxidation states (Collin et al., 2014) and, therefore, acts as an ROS scavenger.

Moreover, a CeO NP with its high Ce³⁺/Ce⁴⁺ ratio mimics superoxide dismutase and produces hydrogen peroxide, but it also mimics catalase activity at a low Ce³⁺/Ce⁴⁺ ratio and shows the scavenging effect (Wang Q. et al., 2012; Wang Z. et al., 2012; Ma et al., 2015; Pulido-Reyes et al., 2015). In addition, the oxidative scavenging effect also is extended to other stresses, which include excess light, heat, and dark chilling. Furthermore, it leads to decrease photosystem II abundance, photochemical efficiency, chlorophyll content, and changed plant morphology (Nievola et al., 2017; Chen et al., 2020; Gao et al., 2020). Wu et al. explained the ameliorative effect of the anionic CeO NPs in the A. thaliana plant against abiotic stress, including excess heat, light, dark, and chilling (Wu et al., 2017b). The salinity stress also imposes a threat to plant physiology by a similar mechanism of oxidative stress. It was found that CeO NPs could alleviate the oxidative stress in Brassica napus. The effect was imposed by NaCl (100 mM) by modifying physiobiochemical properties, such as increased plant biomass, chlorophyll content (which, in
turn, increases the Mg\(^{2+}\) uptake), and efficient photosystem at a concentration of 200 and 1,000 mg/kg (Rossi et al., 2016).

The maintenance of the cytosolic Na\(^+\)/K\(^+\) ratio is considered one of the hallmarks of salinity stress (Hauser and Horie, 2010), and NPs can affect this transport efficiently. Wu et al. demonstrated that nanoceria could augment plant tolerance to salinity stress. By directly acting on hydroxyl radical (·OH) generation and affecting potassium fluxes (reducing K\(^+\) efflux and improving K\(^+\) retention) across the plasma membrane of mesophyll thus improves plant photosynthetic performance and biomass (Wu et al., 2018). The catalytic scavenging activity of CeO NPs has also been utilized to mitigate drought stress, which, in particular, has severe implications for plant growth and yield worldwide. The highly efficient, drought-resistance activity of CeO NPs was observed in foliar-sprayed sorghum plants at a shallow concentration of 10 mg/L.

Additionally, it alleviated the ROS percentage and lipid peroxidation, resulting in improved carbon assimilation rates as well as pollen germination associated with it (Djanaguiraman et al., 2018b). Seedling stage effects of salinity stress could be mitigated by CeO NPs. Seeds primed with poly (acrylic acid)-coated CeO NPs (500 mg/L, in water for 24 h) when germinated in salinity stress (200 mM NaCl) showed drastic effects on the seedling roots, including increased length (56%), weight (41%), and root vitality (114%) as compared to the control. The subsequent perturbation of pathways related to the antioxidative enzyme system, ion binding and Ca\(^{2+}\) signaling, and terpene synthesis result in mitigation of oxidative stress and enhanced tolerance against salinity stress (An et al., 2020).

**Silicon NPs (SiNPs)**

Silicon (Si) is known to be the second most abundant material on Earth after oxygen, and it has gained significant importance in agriculture (Table 1). Si is considered to be midway between an essential and non-essential element for plants because it is not merely responsible for plant survival, but if present, plants can sufficiently benefit (Luyckx et al., 2017). These NPs can directly or indirectly interact with plants, thus conferring morphological and physiological changes in order to provide tolerance against stress. It confers beneficial effects on plant growth; increases their biomass, anatomy, and physiology; modifies tissue differentiation; activates defense systems; and helps in acclimatizing to stress conditions (Babajani et al., 2019).

SiNPs showed anti-stress effects at various concentrations toward drought stress in Hawthorns (Crataegus sp.); the responses varied in the seedlings depending on the concentration applied at different stages of drought stress, i.e., moderate to severe. These effects include enhanced photosynthetic ability; relative water content; membrane electrolyte leakage; and increased levels of chlorophylls, carotenoids, and proline (Ashkavand et al., 2015). The increased tolerance under a
### TABLE 1 | Types of NPs, their relevant sizes, and concentration with the application focus and effect found on alleviating abiotic stress response in plants.

| S.No | NPs            | Size (nm) | Concentration/Plant species | Application         | Effect                                                                 | Type of stress | References                      |
|------|----------------|-----------|-----------------------------|---------------------|----------------------------------------------------------------------|----------------|---------------------------------|
| 1    | TiO$_2$        | 10–25 nm  | 0, 10, 100, and 500 mg/L    | *Linum usitatissimum* | Leaf treatment                                                      |                | Increased carotenoids and chlorophyll content, decreased MDA activity and levels of H$_2$O$_2$ | Drought        | Aghdam et al., 2016             |
| 2    | TiO$_2$        | NA        | 0.01, 0.02, and 0.03%       | *Triticum aestivum* L. c.v *Pishtaz* | Spraying by backpack sprayer                                      | Drought        | Starch content increased, enhanced growth, yield, and gluten | Jaberzadeh et al., 2013 |
| 3    | TiO$_2$        | 7–40 nm   | 0, 2, 5, and 10 ppm         | *Ocimum basilicum* L. | Amended soil                                                            | Cold stress    | Deceased electrolyte leakage index and MDA levels | Mohammadi et al., 2013       |
| 4    | TiO$_2$        | 10–25 nm  | 500, 1,000, and 2,000 mg/kg | *Triticum aestivum*  | Amended soil                                                            | Drought stress | Enhanced seedling dry weight, relative water content, antioxidative enzymes, increased total chlorophyll and carotenoids, improved stomatal conductance, and transpiration rate | Faraji and Sepehri, 2020 |
| 5    | ZnO            | NA        | 0, 0.5, and 1 g/L           | *Glycine max*       | Petri dish exposure                                                   |                | Rate of germination and percentage increased but decreased dry weight | Drought        | Sedghi et al., 2013             |
| 6    | ZnO            | 16–35 nm  | 10 mg/L                     | *Abelmoschus esculentus* L. Moench | Foliar application                                                     |                | Increased photosynthetic pigments, activity of SOD and CAT, reduced proline, and total soluble sugar contents | Salinity stress | Aiaaballah and Alzahrani, 2020 |
| 7    | ZnO and Si     | ZnO 100, SiNP 10–15 nm | 50, 100, 150 mg/L; ZnO NPs and 150, 300 mg/L | *Mangifera indica* L. | Foliar spray                                                            |                | Improved plant growth, nutrients uptake, and carbon assimilation | Salinity stress | Elsheery et al., 2020           |
| 8    | Yttrium doped  | Fe$_2$O$_3$ | 1–10 nm                    | *Brassica napus*     | Nutrient solution                                                     |                | Reduced levels of hydrogen peroxide and MDA, enhanced leaf growth rates, and chlorophyll content | Drought        | Palmqvist et al., 2017          |
| 9    | SiO$_2$        | NA        | 0, 50, 150, and 300 mg/L    | *Solanum lycopersicum* L.| Exposure in vitro                                                      |                | Salt stress genes were up and downregulated significantly help to mitigate the salt stress | Salinity stress | Aminatour, 2016                |
| 10   | Fe$_3$O$_4$    | 20–40 nm  | 0, 30, 60, and 90 ppm       | *Dracocephalum moldavica* L. | Foliar application                                                     |                | Increased leaf area, shoot dry weight, net carbon dioxide (CO$_2$) assimilation rate (A), photosynthesis, Fe concentration, and decreased sodium (Na) content | Salinity stress | Canadad et al., 2017           |
| 11   | SiO$_2$        | NA        | 0, 200, 400, and 600 mg/L   | *Musa acuminata* "Grand Nain" | In vitro                                                              |                | Enhanced shoot growth and chlorophyll content, improved photosynthesis, maintains K$^+$ and Na$^+$ balance, decreases cell wall damage | Salinity and water deficit | Mahmoud et al., 2020           |
| 12   | Fe$_2$O$_3$    | 27.3–34.62 nm | 0, 10, 20, and 30 µM       | *Mentha piperita* L. | Hoagland solution                                                     |                | Reduced proline and MDA levels, the suppressed activity of antioxidative enzymes | Salinity        | Askary et al., 2017             |
| 13   | Fe$_3$O$_4$    | 40–53 nm  | 0.8 ppm                     | *Fragaria × ananassa* Murashige and Skoog medium | Hoagland solution                                                     |                | Enhanced plantlets growth parameters | Salinity stress | Mozafari et al., 2018 |
| 14   | FeSO$_4$       | 99 nm     | 2 g/L                       | *Helianthus annuus* L. c. Alst, Olston, Yourtlor, Hysun96, and Hysun98 | Foliar spray |                              |                | Increased leaf area, shoot dry weight, net carbon dioxide (CO$_2$) assimilation rate (A), photosynthesis, Fe concentration, and decreased sodium (Na) content | Salinity stress | Torabian et al., 2017           |
| 15   | Fe$_3$O$_4$    | 20–40 nm  | 0, 30, 60, and 90 ppm       | *Dracocephalum moldavica* L. | Foliar application                                                     |                | Increased the leaf area, phenolic, flavonoid and anthocyanin content and the activity of guaiacol peroxidase, ascorbate peroxidase, catalase, and glutathione reductase enzymes were enhanced | Salinity stress | Moradbeygi et al., 2020        |
| 16   | FeNPs          | 50–100 nm | 0, 25, 50, and 100 mg/kg   | *Triticum aestivum*  | Potting soil                                                          |                | Improved growth and physiology, enhanced photosynthesis, Fe concentration, and reduced cadmium concentration | Cadmium and drought stress | Adrees et al., 2020             |

(Continued)
| S.No | NPs                          | Size (nm) | Concentration       | Plant species         | Application     | Effect                                                                 | Type of stress            | References                  |
|------|------------------------------|-----------|---------------------|-----------------------|-----------------|----------------------------------------------------------------------|---------------------------|-----------------------------|
| 17   | AgNPs                        | 34 nm     | 25, 50, and 75, 100 mg/L | *Triticum aestivum*  | Potting soil    | Improved root and shoot length, root number, increased morphological growth of the plant-like increased leaf area, and number | Heat stress               | Iqbal et al., 2019          |
| 18   | AgNPs                        | 15–29 nm  | 0, 2, 5, and 10 mM   | *Triticum aestivum*  | Seed priming    | Decreased antioxidative enzyme activity, increased POD activity, proline, sugar content, and dry mass | Salinity stress           | Mohamed et al., 2017        |
| 19   | AgNPs                        | NA        | 0, 10, 20, 30, and 40 µg mL⁻¹ | *Trigonella foenum-graecum* | Petri dish exposure | Enhanced germination rate, improved fresh and dry mass | Salinity stress | Hojjat and Kamyab, 2017 |
| 20   | AgNPs                        | 15–30 nm  | 1 mg/L              | *Triticum aestivum*  | Seed priming    | Wheat germination, growth, induce synthesis of IBA, NAA, BAP contents, and reduced ABA | Salinity stress | Abou-Zeid and Ismail, 2018 |
| 21   | Al₂O₃                        | 5, 30–60, and 135 nm | 50 ppm | *Glycine max* L. cv. *Enrei* | Petri dish exposure | Increased hyocotyle length, glycolysis related protein synthesis, increased mitochondrial membrane protein | Flooding stress | Mustafa and Komatsu, 2016 |
| 22   | Chitosan-PVA and CuNPs       | 95 nm     | 50, 100, and 150 mg/L | *Solanum lycopersicum* L. | Nutrient solution | Increased growth chlorophyll a b content, carotenoids, SOD, Vitamin C and lycopene | Saline stress | Hernández-Hernández et al., 2018 |
| 23   | CuNPs                        | 30–40 nm  | 3.333, 4.444, and 5.556 mg/L | *Zea mays* | Plants priming | Higher leaf water content and plant biomass, increased anthocyanin, chlorophyll and carotenoid contents, increased total seed number, and grain yield | Drought stress | Van Ha et al., 2020 |
| 24   | SeNPs                        | 10–40 nm  | 10 mg/L             | *Sorghum bicolor* (L.) *Moench* | Foliar and water spray | Improved antioxidant system, improved thylakoid membrane integrity, and composition | Heat stress | Djanaguiraman et al., 2018a |
| 25   | SeNPs                        | 8–15 nm   | 0, 1, 4, 8, and 12 µM | *Lycopersicum esculentum* MIL. cv. *Hail!* | Hydroponic solution | Improved shoot fresh, dry weight and diameter, root fresh and dry weight and root volume | Low and high temperature stress | Haghghi et al., 2014 |
| 26   | SiNPs                        | 10–95 nm  | 10 µM               | *Triticum aestivum*  | Nutrient solution | Enhanced antioxidants to protect against UV-B generated oxidative stress | UV-B stress | Tripathi et al., 2017 |
| 27   | MnNPs                        | NA        | 0.1, 0.5, and 1 mg/L | *Capsicum annum* L. | Nanopriming     | Implies the role in plant salt stress management in order to promote sustainable agriculture | Salinity stress | Ye et al., 2020 |
| 28   | Poly(acrylic)-CeO NPs        | 10.3 nm   | ~50 mg/L            | *Arabidopsis thaliana* | Leaf infiltration | Increased quantum yield of photosystem II, carbon assimilation rates and rubisco carboxylation rates to scavenge photosynthesis and ROS | Multiple stress | Wu et al., 2017a |
| 29   | CeO NPs                      | 2.1 ± 1.4 nm | 500 mg/L         | *Gossypium hirsutum* L. | Seed priming    | Decreased ROS levels, improved root parameters, trigger tolerance pathways including ion homeostasis | Salinity stress | An et al., 2020 |
| 30   | MWCNT                        | Diameter: 5–15 nm; Length: ~50 µm | 10, 30, 50, 100, and 200 mg/L | *Dodonaeaviscosa* L. | Nano priming    | Improved seed germination percentage, mean germination time, root and stem lengths, fresh and dry weights of root and stem | Drought stress | Yousefi et al., 2017 |
| 31   | CNTs and graphene            | 13–18 nm  | 50 and 200 µg/ml     | *Catharanthus roseus* | Murashige and Skoog medium | Increased the total number of flowers and leaves | Salinity stress | McGhee et al., 2019 |
| 32   | CNTs and graphene            | 13–18 nm  | 50 and 200 µg/ml     | *Gossypium hirsutum* | Seed priming    | Increased fiber biomass, increased root and shoot growth of young seedlings | Drought stress | Pandey et al., 2019 |
| 33   | Chitosan NPs                 | 10–20 µm  | 0, 30, 60, and 90 ppm | * Hordeum vulgare* L. | Foliar application | Increased the relative water content, the grain yield, the grain protein, the proline content, the CAT and SOD | Drought stress | Bahrboudi et al., 2018 |

*NA, not available.
saline environment conferred by the application of Nano-SiO₂ by accumulating proline maintained the ionic balance, enhanced the antioxidant system, and increased levels of various phytochemicals, thus leading to osmotic adjustments (Soleymanzadeh et al., 2020). Additionally, under salt stress, SiO₂ NPs are shown to increase water use efficiency, stomatal conductance, transpiration rate, and reduced chlorophyll degradation, leading to tolerance from external insult (Haghighi and Pessarakli, 2013). Salt stress is the primary culprit causing significant changes in the epicuticular wax layer.

Interestingly, nano-Si application to strawberry plants resulted in better epicuticular wax structure and thickness as compared to the salt-stressed plant (Avestan et al., 2019). Another work performed on sweet pepper plants (Capsicum annum L.) to study the impact of nano-Si to mitigate salt stress observed significant changes in comparison to their bulk counterpart (Tantawy et al., 2015). Nano-Si was supplied to the plants through an irrigation system at low concentrations (1.0 and 2.0 cm³/L) for weeks, resulting in enhanced leaves and fresh weight. The concentration-dependent effect of SiO₂ NPs was also observed on potato plants exposed to different salt stress (NaCl; 50 and 100 mM). The NPs were able to show better stress amelioration at a lower concentration (50 mg/L) and a higher concentration (100 mg/L) (Gowayed et al., 2017). However, lower concentration was found to be more effective. These studies notably suggest a better viewpoint about the positive and negative impact of NPs, contradicting the assumptions of only toxic aspects of NMs. Therefore, it is required to initially study the characteristics of NPs before employing it in any field.

Plant hormones play a vital role during external stress conditions and confer better adaptation to different changing environmental scenarios (Verma et al., 2016; Raza et al., 2019). A plant growth hormone such as Gibberellin has an important role in plant responses against various abiotic stresses including drought, shading, flooding, and low temperature mainly by reducing the plant growth to divert the focus onto withstanding stress response (Colebrook et al., 2014). Plant hormones can also be supplied to the plant by using NMs; for instance, Mesoporous silica NPs (MSN) entrapping absicic acid were tested on the A. thaliana plant. It significantly showed the prolonged release of hormones and further improved the drought resistance ability of the seedlings (Sun et al., 2018).

Titanium Dioxide NPs (TiO₂ NPs)
We have described the antioxidative effects of specific NPs that scavenge ROS produced in response to threat or stress in plants, but there are other NPs that exert their effects through other mechanisms involving gene regulation (Table 1). For example, TiO₂ NP exposure (0.01%) increased the chlorophyll content and biomass by triggering a mechanism of antioxidant enzyme activities, resulting in decreased malondialdehyde and hydrogen peroxide and production of proline and soluble sugars, thus maintaining the osmotic balance (Abdel Latef et al., 2018). Similarly, nano-TiO₂ was able to trigger the expression of particular essential non-coding RNA considered to play a vital role in the abiotic stress-resistance mechanism. Frazier et al. observed the expression of 11 conserved miRNA in response to TiO₂ NPs (0.1, 1, 2.5, and 5%) in tobacco seedlings that are responsible for rescuing plants from heavy metal stress (Frazier et al., 2014).

Water deficit is a severe issue for plant cultivation as it leads to a loss in vigor and causes severe damage to crops. Nano-TiO₂ can improve the hydration status of the plant by increasing the activity of the nitrate reductase (NR) enzyme, which, in turn, enhances the accumulation of osmolytes. The increased NR enzyme activity results in nitric oxide (NO) production that ultimately induces proline and glycine betaine synthesis (Khan et al., 2020). TiO₂ NPs tend to show both enzymatic as well as a non-enzymatic defense system against stress in plants. Interestingly, TiO₂ NPs are acknowledged for the regulation of other enzymes, such as glutamate hydrogenase, glutamine synthase, and so on, thereby, accumulating more nutrients and also essential oil production (Ahmad et al., 2018). In this regard, Gohari et al. carried out a greenhouse experiment to evaluate the effect of nano-TiO₂ (0, 50, 100, and 200 mg L⁻¹) on Moldavian balm (Dracocephalum moldavica L.) plants grown under exacerbated salinity stress (0, 50, and 100 mM NaCl). The TiO₂ treated plants (100 mg/L) showed a profound effect on the production of essential oil content (1.19%): geraniol, z-citral, geranyl acetate, and geraniol under normal conditions. This implicated protection of aromatic plants against the stress condition by directly modifying their essential oil production profile and composition (Gohari et al., 2020). Karamian et al. carried out another study on medicinal plants showing that drought stress was mitigated by supplying methyl jasmonate (200 μM), salicylic acid (100 μM), and TiO₂ NPs (20 ppm). The results suggest that it increased water stress tolerance through activation of enzymatic and non-enzymatic antioxidant defense systems (Karamian et al., 2020).

**Nano Pesticides**
As more than half of the worldwide population rely on plants and their products for survival, it is a significant concern to enhance plant productivity as well as maintenance of their health. As several biotic and abiotic factors include pathogens, nutrient deficiency, or soil/air pollution, respectively, all equally can affect the health of the plant via inducing damages that, consequently, lead to decreased crop and fruit yield. Frequently, plant disease is caused by a broad range of disease-causing organisms (or pests). Thus, it is an immediate requirement to keep them from causing more plant wilting. Insects are crucial matters in agriculture as they demolish crops and overrun stored food, consequently causing the worsening quality of food and transmission of plant diseases. As per the definition of the U.S. Environmental Protection Agency, pesticides are substances that deliberately prevent, repel, and demolish any pest (Figure 3).

Pesticides are used to enhance and improve the crop yield and efficiency by protecting plants from damaging factors, including plant diseases and insects (Jampílek and Králová, 2017). However, it has been found that the use of pesticides is lethal and toxic for the environment; most of them are hazardous and lethal to human and animal health. Therefore, many pesticides are banned by state or international authorities. This involves several significant and vital issues, including
indiscriminate use of pesticides at a high concentration that harms the ecosystem, increasing bioaccumulation, making the soil infertile, and disrupting its microbiota (Meena et al., 2020). Some issues must be taken into consideration to increase agronomic productivity and efficiency and reduce the environmental effect (Figure 3).

The synthesis of effective and safe pesticides is tricky and expensive, but nanotechnology provides a novel and improved solution (Sasson et al., 2007). Nanotechnology already has a significant impact on pharmacy (drug delivery). With the recent developments in the agriculture and food sector, it is promising. Nanotechnology is not restricted to applications for plant protection against pests, but expands to minimize waste, monitor of plant growth, guarantee enhanced food quality, and secure rising of global food production (Jampilek and Králova, 2017). The most frequent trials in nano pesticides are nano herbicides, nano insecticides, nano nematocides, and nano fungicides (Table 2).

The best example of a nano insecticide is nanostructured alumina (NSA), which is nanoengineered material that works as an insecticide. It is synthesized through the oxidation of metal, which exhibits a fixed electric charge. Advance nanotechnology designed NSA in such a way so it can combat insects by taking advantage of its system. Insects show electric charges, which are created through triboelectrification. Tribo-charge is a type of contact electricity or electrification generated by two non-conductive bodies or material when they come in contact through friction. Furthermore, an exciting mode of action of NSA takes advantage of insect tribo-charging and is completed in two sequential mechanistic steps. Primarily, negatively charged NSA particles initiate interaction with a positive charge of the insect through strong electrical bonding. This interaction causes dehydration of the insect through the potent sorptive property of the NSA particle, which detaches insects’ cuticle insect layer, a fibrous composite of chitin and results in the death of the insect due to dehydration. As hypothesized, the insecticidal property of NSA powder or particle is based on the attachment of the particle to the cuticle of the insect, which further disturbs the water balance and leads to ambient increased humidity. The strong insecticidal efficacy of NSA relies on its small size, intrinsic electric charge, sorbative prosperity, and large surface area (Stadler et al., 2018; Figure 4).

Moreover, engineered nano pesticides are assisting the conventional cotton and insect-resistant transgenic (Bt cotton) crop, which was designed to combat the bollworm. Insecticidal activity of Cu NPs at a low dose (10 mg/L) has the potential to upregulate the expression of exogenous microbial protein from Bacillus thuringiensis coded through the Bt toxin in plant tissue to improve resistance against the bollworm (Zhao et al., 2020; Table 2). During spot disease in tomato plants, TiO2 and ZnO NPs, photochemically active, act as antimicrobial agents. When TiO2 and ZnO NPs (photochemically active) are exposed to light, they generate excited electrons, which, in the presence of oxygen, synthesize superoxide radicals through direct electron transfer. Using photochemically active TiO2, NPs are engineered to have antimicrobial properties and have a great impact on agriculture as nano pesticides. It has extensive photocatalytic activity and higher antibacterial potential against X. perforans, which causes spot disease in tomato plants (Paret et al., 2013).

Furthermore, the packaging of conventional pesticides with NPs or polymers is highly demanding in the area of the pesticide industry as they are anticipated to address these issues by enhancing pesticide efficiency, increasing production, reducing excess runoff by slow release of active ingredients over a prolonged period (Nuruzzaman et al., 2016), and ultimately protecting the environment. This new field of research comprises the study of the interaction of NPs with insects to improve existing pest control management and provide advanced nanoformulations that remain stable, quickly penetrate the organism, are delivered at the targeted site, are cost-effective, and are more active during field applications. Nanoformulation or nano carriers act as the vehicle to transport and control delivery or release of the active compound, which presents in its core, and is used to conserve an adequate amount of compound during the whole period of insect growth (from the transition from larva to the maturity stage). For instance, sustainable nano carrier construction of chitosan liposome, which coats the inner core, consists of etofenprox or alpha-cypermethrin. Similarly, different types of NMs and nanoformulations of conventional pesticides have been developed that show a significant impact on pest control (Figure 4).

Nanoemulsions
Nanoemulsions refers to the oil-in-water emulsion in which pesticide is dispersed as nanosized droplets in water. The main advantage of producing nanoemulsions is to increase the solubility of pesticidal active ingredients. The nanoemulsions of neem oil show that smaller droplets are efficiently taken up as LC50 is found to be decreased with droplet size (Anjali et al., 2012). However, the higher efficacy of the permethrin nanoemulsion than that of permethrin macroparticles against yellow fever mosquito (Aedes aegypti) is indicative of its enhanced uptake (Kumar et al., 2013). In one study, it is reported that Emamectin-benzoate nanoemulsion is more effective against the Asian rice borer (Chilo suppressalis) compared to coarse emulsions (Fan et al., 2010). In some reports, no significant results were obtained with pesticide colloids, for example, no significant difference in LC50 values was found for nanoemulsion of Chlorpyrifos and a commercially available coarse emulsion against cotton bollworm (Helicoverpa armigera) (Qi-liang et al., 2006). Another important aspect is their controlled or slow release from the colloidal formulations that result in more sustained and prolonged exposure (Figure 4).

Polymer Nano Pesticides
These are polymer-based nanocarriers for encapsulating pesticides that act as a protective reservoir containing polysaccharides and polyesters. In addition to this, they tend to increase dispersion in aqueous media, facilitating the slow and controlled release of pesticides. The polymer nano pesticides have gained lots of attention as they are flexible to design, biodegradable (corn oil, beeswax, and cashew gum), and biocompatible. Polymer-based nanoformulations such as
| S.No | Nanomaterial | Name nanoparticles | Concentration | Pest | Plant disease | Advantage | References |
|------|--------------|--------------------|---------------|------|--------------|-----------|------------|
| 1    | Ag-Based NPs | DNA directed silver (Ag) nanoparticles grown on graphene oxide (GO) AgNPs | 16 mg/L | Xanthomonas perforans | Bacterial spot of tomato | Significantly decreased the activity of cultured *Xanthomonas perforans* | Ocsoy et al., 2013 |
| 2    | AgNPs        | (30–150 mg/mL) Meloidogyne spp. | 99% of the nematodes died within 6 d |  |  |  | Cromwell et al., 2014 |
| 3    | AgNPs        | 150 mg/mL Meloidogyne spp. | Reduced the number of nematodes by 82 and 92% at day 2 and day 4, respectively, in field |  |  |  | Cromwell et al., 2014 |
| 4    | Serratia sp. biosynthesized AgNPs | Bipolaris sorokiniana | The spot blotch pathogen of wheat | Several wood-degrading fungi | Biosynthesized AgNPs exhibited strong antifungal activity | Mishra et al., 2014 |
| 5    | Turnip leaf extracted green-synthesize AgNPs | Gloeophyllum abietinum, *G. trabeum*, Chaetomium globosum, and Phanerochaete sordida | 10 mg/L Phytophthora | Hydromelium ovescica f.sp. niveum | Suppressed Phytophthora infection on plants and improved plant survival | Narayanan and Park, 2014 |
| 6    | Artemisia absinthium extracted green-synthesize AgNPs | 50 mg/L | Phytophthora infection |  |  |  | Ali et al., 2015 |
| 7    | Cu-Based NPs | Cu(OH)\(_2\)NPs (Kocide 3000) | 1,000 mg/L Escherichia coli and Bacillus subtilis as well as the plant fungal pathogens *F. oxysporum*, *C. lutea*, *A. alternata*, and *P. destructiva* | Antibacterial efficiency of CuNPs vs. the traditional fungicide bavistin (Devistin, carbendazim 50% WP) demonstrated the better performance of CuNPs | Yoon et al., 2007 |
| 8    | Cu\(_2\)(PO\(_4\))\(_2\)_3H\(_2\)O nanosheets | 10 mg/L Fusarium oxysporum f.sp. niveum | Suppress root fungal disease in watermelon (*Citrus limon*) | 56% decrease in disease progression | Borgatta et al., 2018 |
| 9    | CuNPs and K\(_2\)SiO\(_3\)NPs | 50 mg/L CuNPs + 184 mg/L Si; 50 mg/L CuNPs + 460 mg/L Si; 250 mg/L CuNPs + 184 mg/L Si; and 250 mg/L CuNPs + 460 mg/L Si Clavibacter michiganensis | Reducing the severity of C. michiganensis infection on hydroponically cultivated tomato plants | Combined application of the two particle types stimulated the levels of the enzymatic and non-enzymatic metabolites essential for the defense of tomato plants and thus increased the tolerance of C. michiganensis | Cumplindo-Nájera et al., 2019 |
| 10   | CuONPs       | 10 mg/L S. littoralis | Insecticidal activity on Bt-transgenic cotton and conventional cotton | Enhanced the expression of exogenous genes encoding Bt toxin in cotton plant tissues | Ayoub et al., 2018 |
| 11   | CuNPs        | Lethal concentration 50 (LC50) of 232 mg/L after 3 d, whereas for CaO NPs an LC50 of 129 mg/L was achieved 11 d post-treatment S. littoralis | Insecticidal activity on Bt-transgenic cotton and conventional cotton | Cu NPs exhibited faster entomotoxic effects than achieved with CaO NPs | Ayoub et al., 2018 |
| 12   | Carbon-Based NPs | SWCNTs, multiwalled carbon nanotubes (MWCNTs), graphene oxide (GO), reduced graphene oxide (rGO), fullerene (C60) | 62.5, 125, 250, and 500 mg/L Fusarium graminearum and Fusarium poae | At 500 mg/L, O60 inhibited the spore germination of F. graminearum but not with F. poae | Strongest antifungal activity was exhibited by SWCNTs (500 mg/L), followed by MWCNTs (500 mg/L), GO (500 mg/L), and rGO (500 mg/L), whereas the AC at this tested concentration range showed no antifungal effect. These particles induce inhibition of water uptake and the induction of plasmolysis | Wang et al., 2014 |
| S.No | Nanomaterial       | Name nanoparticles                                                                 | Concentration     | Pest                  | Plant disease                                                                 | Advantage                                                                                                                                                                                                 | References               |
|------|-------------------|--------------------------------------------------------------------------------------|-------------------|-----------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| 13   | Ti-Based NPs      | TiO$_2$NPs (Photochemically active)                                                  | 500–800 mg/L      | X. perforans          | The pathogen that induces spot disease in tomato plants                        | High photocatalytic activity and antibacterial potential to reduced bacterial spot severity                                                                                                               | Paret et al., 2013       |
| 14   | Ce-Based NPs      | CeO$_2$NP                                                                            | 50 and 250 mg/L   | Fusarium wilt         | Mediated suppression of in tomato                                               | 250 mg/L CeO$_2$NPs significantly reduced disease severity, by 53% and 57%, respectively                                                                                                                 | Adisa et al., 2018       |
| 15   | Mg-Based NPs      | MgONPs                                                                               | 0.1, 0.5, 0.7, or 1% (growth media: 50% vermiculite and 50% perlite) | Ralstonia solanacearum | Resistance of tomato plants to Ralstonia solanacearum                          | The pretreatment of tomato roots with MgONPs suspension (0.1, 0.5, 0.7, or 1%) significantly reduced the incidence of disease. The mechanism included the upregulation of salicylic acid-inducible PR1, jasmonic-acid-inducible LoxA, ethylene-inducible Osm, and systemic-resistance-related GluA | Imada et al., 2016       |
| 16   | MgONPs            | 200 or 250 mg/L                                                                       | R. solanacearum   | Induced tobacco bacterial wilt                                                | Effectively suppressed R. solanacearum, which induced tobacco bacterial wilt. Proposed mechanism included physical injury of cell membranes and ROS accumulation                                               | Imada et al., 2016       |
| 17   | Synthesized Mg(OH)$_2$NPs |                                                                                  | X. alfalfae, Pseudomonas syringae, and E. coli | Inhibited the growth of X. alfalfae, Pseudomonas syringae, and E. coli within 4 h. The killing activities of Mg(OH)$_2$NPs were comparable to those of Kocide 3000, thus demonstrating their potential as a Cu alternative |                                                                                                                                                                                                                                                              | Huang et al., 2018       |
| 18   | Si-Based NPs      | SiNPs                                                                                | 15 kg/ha/20–40 nm | Aspergillus spp.          | Phytopathogen resistance of maize                                               | Triggered the pregulation of phenolic compounds, resulting in the greater resistance of the plants to Aspergillus spp.                                                                                      | Suriyaprabha et al., 2012 |
| 19   | Mesoporous silica nanoparticles (MSNs) with a chitosan coating (CTS-MSNs) or without | 36 nm, 500 mg/L                                                                 | Fusarium wilt     | Suppress Fusarium wilt in soil-grown watermelon                             | Both MSNs and CTS-MSNs reduced disease severity, by 40 and 27%, respectively                                                                                                                              | Buchanan et al., 2019    |
| 20   | Mn-Based NPs      | MnONP                                                                                | 1 mg/L /40 nm     | Fusarium oxysporum f.sp. lycoperici                                         | Tomato disease                                                                  | Reduced disease estimates [area under the disease progress curve (AUDPC)] by 28% in plants grown in soil                                                                                                    | Elmer and White, 2016    |

(Continued)
| S.No | Nanomaterial | Name nanoparticles | Pest | Plant disease | Advantage | References |
|------|-------------|-------------------|------|--------------|-----------|------------|
| 21   | Nanoformulations of conventional pesticides | Tebuconazole | Rust and molds | Leaf senescence and decay | 50% improvement in release rate | Mattos and Magalhães, 2016 |
| 22   | Porous hollow silica | Validamycin | – | – | Loading capacity improved up to 36% | Liu F. et al., 2006 |
| 23   | Calcium carbonate | Validamycin | Rhizoctonia solani | Controlled release up to 2 weeks | Qian et al., 2011 |
| 24   | Porous hollow silica | 2,4-dichlorophenoxyacetate | – | – | Improved herbicide activity period | Bin Hussein et al., 2005 |
| 25   | Lignin | Diuron | – | – | Improved controlled release rate | Yearla and Padmasree, 2016 |
| 26   | Other nanomaterials | Silver (Ag) NPs | Xanthomonas campestris pv. campestris | Bacterial blight | Significant reduction of bacteria | Rajesh et al., 2012 |
| 27   | Ag core-DHPAC shell nanocluster | Phytophthora capsici, Phytophthora nicotianae, and Phytophthora colocasiae | Fungal disease | Up to 80% of growth inhibition | Ho et al., 2015 |
| 28   | Chitosan NP | Rhizopus sp., Colletotrichum capsici, Colletotrichum gloeosporioides, and Aspergillus niger | Disease in Chile | Delayed mycelia growth | Chookhongkha et al., 2012 |
| 29   | Chitosan NP | Alternaria alternata, Macrophomina phaseolina, and Rhizoctonia solani | Fungal disease | Inhibited spore germination | Saharan et al., 2013 |
| 30   | Iron oxide (FeO) NP | R. solani, B. cinerea, and F. oxysporum | Fungal disease | 60-80% of fungal inhibition | Chhipa and Kaushik, 2015 |
| 31   | Copper (Cu) NP | Fusarium sp. | Fungal disease | Antifungal activity | Bramhanwade et al., 2016 |
| 32   | Copper (Cu) NP | Xanthomonas axonopodis pv. punicae | Pomegranate bacterial blight | Inhibited bacterial growth | Mondal and Mani, 2012 |
| 33   | Copper (Cu) NP | Phytophthora infestans | Disease in tomato | Active at low concentration of antifungal agent | Giannousi et al., 2013 |
Advantages of nano-based agrochemicals: Nano fertilizers provide nutrients to plants or enhance the effect of fertilizers even when applied in smaller amounts. Uptake of nutrients can be increased by encapsulating the fertilizers in nanoform. Ultimately, it reduces nutrient loss, improves crop quality and yield, and minimizes the risk of environmental degradation.

Solid NPs as Nano Pesticides
Some NPs that are considered to be antibacterial/pesticidal agents instead act only as nanocarriers, for example, inert dust of alumina, silica, and clays that damage the inner wax coating of the insect cuticle, which, in turn, loses water and dies due to desiccation. This mode of action is considered safer as it is unlikely that insects will develop resistance (Shah and Khan, 2014). SiNPs cause damage to the protective epidermis layer by being physio-sorbed on the lipids, thus causing the death of the insects (Barik et al., 2008). Nanostructured alumina was discovered by Stadler et al. (2010) as an insecticide against two grain pests, *R. dominica* and *S. oryzae*. The thin sheets of silicate materials are nanoclays that are produced from volcanic ash. They have been efficiently used as a carrier for controlled release of a potent herbicide 2,4-dichlorophenoxyacetate bin (Bin Hussein et al., 2005).

Nanoherbicides
Weeds are considered to be the biggest threat for damaging crops in a greater quantity by utilizing nutrients that would otherwise be available to plants. Conventional methods, including removing weeds by hand, for eradicating weeds is time-consuming and requires a lot of effort. Many herbicides are currently available in the market that have the potential to kill weeds in a field but also cause harm to the crops and decline the soil fertility. Nanoherbicides can be a better, eco-friendly alternative for effective weed control without leaving any toxic residues in the soil (Pérez-de-Luque, 2017; Table 2). Constant use of the same herbicide for a more extended period could lead to resistance in the weeds. Poly (epsilon-caprolactone) (PCL) nanocapsules have been used as a carrier system for the conventional herbicide atrazine. The atrazine-containing nanocapsules showed more potent post-emergence herbicidal activity on mustard plants than a commercial atrazine formulation (Oliveira et al., 2015). Chitosan NPs were prepared by cross-linking through disulfide bonds of diuron for its controlled delivery based on the concentration of glutathione (Yu et al., 2015).

Nanofungicides
Fungal diseases are the most common and account for more than 70% of damage to major crops such as rice, wheat, barley, groundnut, and cotton (Godfray et al., 2016). These diseases affect society by causing severe loss to crop yield and the economy. Conventional fungicides work to curb these losses but, on the other hand, target non-specific living organisms and cause imbalance to the biodiversity. Therefore, we need to look for alternate approaches to achieve better precision in fungal disease management (Patel et al., 2014). One of the best approaches is the development of NPs as an effective strategy against fungal...
pathogens. AgNPs, owing to their antimicrobial properties, are widely used for disinfection purposes (Baker et al., 2005). An experiment was conducted to check the effectiveness of AgNPs and Ag ions on plant-pathogenic fungi Bipolaris sorokiniana and Magnaporthe grisea. The ionic and nanoparticulate forms were effective against fungi and significantly reduced disease severity when applied for 3 h (Jo et al., 2009). CuNPs and AgNPs can both suppress the growth of two fungal pathogens Alternaria alternata and Botrytis cinerea (Ouda, 2014). ZnO NPs and MgO NPs show antifungal activity against Alternaria alternate, Rhizopus stolonifer, Fusarium oxysporum, and Mucor plumbeus (Wani and Shah, 2012). An MWCNT-g-PCA hybrid material encapsulated two conventional pesticides, zineb and mancozeb, which was confirmed to be a more potent fungicide against A. alternate (Sarlak et al., 2014).

Nano Fertilizers

Currently, agriculture all across the globe faces a broad spectrum of challenges, such as nutrient deficiency, stagnation in crop yields, diminishing soil organic matter, low water availability, nutrient deficiency in the soil, decreased land area due to urbanization and land degradation, and labor shortages (Godfrey et al., 2010). The application of nanoscience and nanotechnology is increasing tremendously, and novel methods are continuously being proposed to produce novel and desirable materials for crop production and management (Table 3). It is one of the most influential ideas of the evolving science of precision agriculture in which farmers efficiently make use of fertilizers and other inputs. The uncontrolled population has prompted the enormous production of conventional fertilizers to increase food production and crop protection, but this ultimately decreases the soil fertility and quality of food. These chemical fertilizers not only add to the tribulations of the subtle ecosystem, but also affect human health as they remain unused. The global demand for fertilizers is expected to rise in the coming years, according to a report submitted by the Food and Agricultural Organization of the United Nations. Therefore, it is imperative to involve intelligent strategies for sustainable agriculture, such as nanotechnology. Nano fertilizers are environmentally friendly fertilizers or smart fertilizers with the potential to increase the application rates of fertilizers and reduce the loss of nutrients from it, mainly phosphorous and nitrogen (Dimkpa and Bindraban, 2017). It offers the gradual and controlled release of nutrients to the targeted site, which helps to prevent the contamination of water bodies and the environment (Dwivedi et al., 2016; Figures 2, 3).

Nano fertilizers are those that either provide nutrients to plants or enhance the effect of fertilizers even when applied in smaller amounts (Rameshiaiah et al., 2015). Uptake of nutrients can be increased by encapsulating the fertilizers in nano form that ultimately reduces nutrient loss, improves crop quality and yield, and also minimizes the risk of environmental degradation (Figure 2). The foliar application of these nano fertilizers is also demonstrated to mitigate the stress in plants (Tarafdar et al., 2012). Nano fertilizers can be divided into three categories based on the nutritional requirements of the plants: (1) macronutrient nano fertilizers, (2) micronutrient nano fertilizers, and (3) nanoparticulate nano fertilizers (Chhipa, 2017). Macronutrient nano fertilizers are composed of a combination of elements, such as potassium (K), magnesium (Mg), nitrogen (N), calcium (Ca), and phosphorus (P). It is estimated that the total consumption of macronutrient fertilizers is projected to increase to 263 million tons (Mt) in 2050, thus showing a critical need for these fertilizers in the agricultural sector. Delfani and his group tested the efficiency of Mg and Fe NPs on the growth of black-eyed peas (Vigna unguiculata) by foliar application and observed enhanced seed weight and photosynthetic ability that, in turn, increased the yield (Delfani et al., 2014). The Ca NPs, together with humic acids, improved seedling growth in peanuts (about 30% increase) with dry biomass reaching 5.78 g per plant (Liu et al., 2005). The synthesized hydroxyapatite (Ca$_5$ (PO$_4$)$_3$ OH) NPs of size 16 nm significantly enhanced the growth rate and yield of soybeans (Glycine max) in comparison to control. These studies suggest that NPs can be applied as potent fertilizers for field crops (Liu and Lal, 2015). For more detail, please refer to Table 3.

Plant micronutrients consist of molybdenum (Mo), copper (Cu), iron (Fe), nickel (Ni), manganese (Mn), and Zinc (Zn), and compared to macronutrients, they are required in much smaller amounts for the healthy growth of crops. Micronutrients applied as composite formulations are more effective in providing enough nutrients and cause less environmental degradation. Micronutrients packed in NPs enhance the nutrient bioavailability and fertilizer use efficiency relative to other conventional ions and salts (Dimkpa and Bindraban, 2016). The composite of three micronutrients NPs (ZnO, CuO, and B$_2$O$_3$) has been successfully established for agronomic fortification to mitigate drought stress in soybean plants (Dimkpa et al., 2017a). Nanoparticulate fertilizers contain other NPs, such as CNTs, TiO$_2$, and SiO$_2$, that enhance the growth of plants. The mixture of TiO$_2$ and SiO$_2$ increased nitrogen fixation, growth enhancement, and improved seed germination in soybeans (Lu et al., 2002; Table 3).

Molecular Mechanism of Nano Fertilizer Uptake, Translocation, and Action

Use of NM as nano fertilizer is possible due to its smaller size than the pore size of the plant cell wall (up to 20 nm), which contributes to nutrient uptake. Nano fertilizers can directly apply to soil and/or leaves. Therefore, there are two significant modes of application of nano fertilizer. First is foliar entry, and second is root entry. Spray on the trough cuticle, stomata, hydathodes, lenticels, and wounds leads to the foliar entry, and root tips, lateral root, root hairs, and rhizodermis provides the root entry. Foliar applications of nano fertilizer prefer or can be done during unfavorable soil and weather conditions (Figure 1). Additionally, this mode of application promotes the direct entry of nutrients into the plant leaf system, simultaneously reducing the wastage of fertilizer. Hence, foliar application of nano fertilizer leads to higher NUE and also gives a rapid response to the growth of crops or plants (Mahil et al., 2019). Foliar entry is facilitated by nano-pores, the base of the trichome and stomal opening in leaves, easing NP uptake and their transport inside of leaves. For instance, in faba beans (Vicia faba) and more (in C. arabica below 2.5 nm and P. cerasus below
### TABLE 3: Different types of NPs employed for the generation of nano fertilizers, their composition, benefits, and examples of active components.

| S.No | Engineered metal nanomaterials | Nano fertilizer | Concentration/size | Plant | Output/ advantage | References |
|------|---------------------------------|-----------------|--------------------|-------|-------------------|------------|
| 1    | Fe-Based NPs                    | FeOXNPs         | Seedlings were cultivated in aqueous medium spiked with 5–20 mg/L | Lettuce (Lactuca sativa) | Significantly increased the shoot length of lettuce, by 12–26% | Liu et al., 2016 |
| 2    | Fe₂O₃NPs                        | 30–60 mg/L      | Soybean (Glycine max L., Oxley) | Significantly increased the chlorophyll content of hydroponically cultivated soybean | Ghafariyan et al., 2013 |
| 3    | γ-Fe₂O₃                         | Cultivation of maize seedlings in a hydroponic solution containing 20 mg/L | Maize (Zea mays) | Significantly increased the germination rate and the root length, by 27.2 and 11.5%, respectively. Even at an extremely low dose, iron oxide NPs exert positive effects on plant growth | Li et al., 2016 |
| 4    | α-Fe₂O₃NPs                      | Presoaking the plants with the particles at a dose as low as 5.54 x 10–3 mg/L | Legumes | Significantly increased root length, by 88–366%. Effectiveness of Fe₂O₃NPs as a replacement for traditional Fe-based fertilizers | Palchoudhury et al., 2018, Rui et al., 2016 |
| 5    | Citric-acid-coated nano-Fe₂O₃   | Soybean         | Foliar spray of citric-acid-coated nano-Fe₂O₃ significantly enhanced root length and the photosynthetic rate | Alidoust and Isoda, 2013 |
| 6    | γ-Fe₂O₃                         | Plants were cultivated in soil spiked with 2 mg/kg concentrations of γ-Fe₂O₃ (20 nm) for 38 d | Peanut (Arachis hypogaea) | Significantly enhanced their rate of photosynthesis and their biomass | Alidoust and Isoda, 2013 |
| 7    | Zn-Based NPs                    | ZnONPs          | Mung bean (Vigna radiata) | Foliar application of the particles increased the biomass of the roots and above-ground tissues of the seedlings | Dhoke et al., 2013 |
| 8    | ZnONPs or Zn salt amendment     | Sorghum (cereal) | Efficacies of two exposure pathways (soil and foliar). Foliar application of both ZnO and Zn salt significantly increased sorghum productivity and grain nutritional quality under both low and high NPK input (NPK indicates nitrogen, phosphorous, and potassium) | Dimkpa et al., 2017b |
| 9    | ZnONPs                          | Concentrations ranging from 50 to 2,000 ppm/(25 nm) | Maize | At a concentration of 1,500 ppm, ZnONPs significantly increased the germination percentage (by 80%) and the seedling vigor index. The highest grain yield (3,298 kg/ha) was obtained with ZnONPs at a dose of 400 ppm. Besides its beneficial role in plants under non-stress conditions, ZnO nanoparticles also improved plant performance under salinity stress, drought, and Cd stress | Subbaiah et al., 2016 |
| 10   | Cu-Based NPs                    | Cu-chitosan NPs | 0.04–0.12%         | Maize | Enhanced maize seedling growth by increasing both the activity of α-amylase and the starch content | Saharan et al., 2016 |
| 11   | Mg-Based NPs                    | MgNPs           | Foliar-sprayed of a dose of 0.5 g/L | Black-eyed pea | Significantly increased photosynthesis and the biomass of the plants. However, the MgNPs altered cell membrane permeability | Defrani et al., 2014 |
| 12   | MgNPs                           | Foliar spray of 20 mg/L (<2 micron) | Tobacco | Increases in root length, tip number, and root biomass. The mechanism was attributed to the MgNP-induced enhancement of solar energy absorption of the leaves | Rathore and Tarafdar, 2015 |
| 13   | MgONPs                          | 50, 150, and 250 mg/L | Tobacco | Improved SOD and POD activities in grown in matrix media | Cai et al., 2018 |

(Continued)
| S.No | Engineered metal nanomaterials | Nano fertilizer | Concentration/size | Plant | Output/ advantage | References |
|------|--------------------------------|----------------|-------------------|-------|-----------------|------------|
| 14   | Mn-Based NPs                  | MnNPs and MnSO₄ | Cultivated in Hoagland's nutrient solution with MnNPs or MnSO₄ for 15 d at 0.05 mg/L | Mung bean | Significant increases in the fresh and dry biomass (39.0 and 53.6%, respectively) and in root and shoot length of mung bean. Also, greater photophosphorylation and increased oxygen evolution in chloroplasts were treated with MnNPs than in control and MnSO₄-treated chloroplasts | Pradhan et al., 2013 |
| 15   | Mo-Based NPs                  | MoS₂           | Foliar application, 32–500 µg/mL (1.5 µm) | Rice | MoS₂ (125 mg/L) significantly increased rice plant biomass and the chlorophyll content of the leaves. MoS₂ also upregulated the expression of the rice aquaporin gene | Li Y. et al., 2018 |
| 16   | Si-Based NPs                  | SiO₂ NPs       | 8 g/L (~12 nm) | Tomato (L. esculentum Mill. cv. super strain B) | Significantly enhanced seed-germination-related parameters, such as seed germination, mean germination time, seed germination index, and seedling fresh weight | Siddiqui and Al-Whaibi, 2014 |
| 17   | Nanosilicon dioxide (SiO₂ NPs) | 100 mg/L/(10–20 nm) | Improved plant growth rate and productivity in Strawberry plants [grown in coco peat and perlite (2/1, v/v) under salinity stress] | | | Avestan et al., 2019 |
| 18   | SiO₂ NPs                      | Foliar spray of 3,200 mg/L | Cotton | Improved growth performance of cotton plants under drought | | Shalain et al., 2016 |
| 19   | MSN-Based NPs                 | MSNs           | 0–2,000 mg/L | Wheat and lupin plants | MSNs taken up by the roots were translocated to chloroplasts, where they significantly increased photosynthetic activities. MSNs at doses of 500 and 100 mg/L enhanced seed germination and increased plant biomass, total protein, and chlorophyll content. Even the highest MSNs concentration (2,000 mg/L) did not result in oxidative stress or cell membrane damage | Sun et al., 2016 |
| 20   | TiO₂-Based NPs                | Nano-TiO₂      | 0.25%, originated from 1 mL of Ti(OC₄H₉)₄ | Arabidopsis thaliana | Significantly increased the expression of the light-harvesting complex IIb (LHCBIIb) gene and LHCBII III in the thylakoid membranes of (grown under agar medium). Also, absorption peak intensity of chloroplasts in the red and blue regions was significantly increased by TiO₂ NPs | Ze et al., 2011 |
| 21   | SWCNT-Based NPs               | SWCNTs         | 5 mg/L | Spinach leaves | Enhanced the photosynthetic activities of whole spinach leaves by 31%, by increasing the electron transfer rate | Giraldo et al., 2014 |
| 22   | Others                        | Quantum dots (CQDs) | 50, 54.2, and 75 mg/L | Mung bean | Promote acyclic photophosphorylation, ATP synthesis, and oxygen release in isolated mung bean chloroplasts. The resulting enhancement of photosynthesis by accelerated electron transfer rate in thylakoid membranes | Chandra et al., 2014 |
100 nm), it is demonstrated that nanosized particles (43 nm), deeply buried in the bulk of the leaf interior compartment, which suggests the effectiveness of nano fertilizer to enhance nutrient uptake (Eichert et al., 2008).

As nano fertilizer, it is suggested for higher nutrient use efficiency (NUE) because of its higher ability to pass and deliver the nutrients via nanosized (50–60 nm) pores of plasmodesmata, which usually transports ions between cells (Iqbal, 2019). Furthermore, plant root entry also shows significant passage for nutrient uptake, such as being highly porous to nano fertilizer compared to conventional fertilizer or manure. Demonstration using fluorescently labeled monodispersed mesoporous silica NPs suggest they amazingly describe the mechanism of uptake and translocation of the NP. NPs penetrate the root through symplastic and apoplastic pathways and passes to the xylem tissue to areal regions of the plant, such as the leaves and stem (Sun et al., 2014). For instance, ZnO and CeO₂ NPs are illustrated by tracing travel patterns from the entrance into the ryegrass root cells and further up to the vascular tissues in soybeans (Glycine max) (López-Moreno et al., 2010). Once entered into the cell, these particles take the way through apoplastically or symplastically, where they travel through the plasmodesmata of one cell to another and finally reach the cytoplasm. In the cytoplasm, they begin to distribute to different cytoplasmic organelles and participate in various metabolic pathways of cells. Also, a higher uptake of NPs in the hydroponic medium as compared to plants grown in the sand has been noticed (Solanki et al., 2015). Hence, nano fertilizers have great potential to transport and deliver nutrients via a smaller channel of plasmodesmata (50–60 nm) from cell to cell. Therefore, higher NUE and less nutrient loss during entrance to transport by nano fertilizer results in higher productivity, ~6–17%, and increased nutritional quality of field crops and plants (Iqbal, 2019; Figure 1).

SENSING SYSTEM WITH NPs

The uncontrolled use of pesticides, fertilizers, and heavy metals in agricultural practices needs to pay attention to minimize the loss to the environment. Regular monitoring of the health status of soil and possible occurrence of any disease must be done with the help of emerging technologies. Accurate sensing systems must be developed that should be handy and portable for real-time monitoring of large field areas. Nanotechnology could enhance the performance of any biosensor to agree with its real application in agriculture. Remarkable progress in the nanofabrication technology and sensitive analytical techniques enables responsive sensor development. Nano sensors could demonstrate their potential in many areas, such as crop cultivation and harvesting, pathogen detection, and soil parameters (pH and nutrients), to name a few. NPs have unique surface chemistry, electrical and thermal characteristics, enhanced sensitivities, and enhanced detection limits that make them suitable for better sensing systems (Yao et al., 2014).

NP-Based Biosensor for Pesticide Residue Detection

Traditional methods often employed for pesticide detection, such as high-performance liquid chromatography and GC/MS, are highly reproducible but suffer from low detection limits and require more efforts (sample collection, extraction, analysis) and well-equipped laboratories (GC/MS pesticide detection). The pesticide, heavy metals, and other pollutants present in water and soil are detected by various NMs, such as metal NPs, graphene, CNTs, and QDs (Zhang and Fang, 2010). The use of NMs adds the further advantages of high sensitivity, low sample requirement, and faster detection. The binding of the target molecule with that of the biosensor can be measured by various direct and indirect means, such as recording changes in color, electrical potential, or fluorescence. Another strategy is array-based, in which biomolecules can be fixed to a substrate and allows simultaneous measurement of multiple analytes (Ghormade et al., 2011). NMs such as cadmium telluride (CdTe) QDs were employed for the detection of 2,4-dichlorophenoxyacetic acid based on a fluororimmunoassay-based sensing system (Vinayaka et al., 2009).

Furthermore, the fluorescent property of QDs, owing to their high photostability and size-tunable emission properties (Vinayaka and Thakur, 2010), can also be exploited for the detection of other harmful pesticides, such as atrazine (Cummins et al., 2006), pyrethroid (Kranthi et al., 2009), and methiocarb (Hua et al., 2010). The optical-based immunosensors employ several NMs, including QDs and AuNPs, that give enhanced signal amplification. Chen et al. employ QDs conjugated with streptavidin for detecting the pesticide chlorpyrifos in drinking water (Chen et al., 2010). AuNPs can be used for detecting onsite pesticides found in water coming from agricultural fields and other resources (Lisha and Pradeep, 2009). AuNP function is realized for immunochromatographic test strips for the detection of different pesticides. The authors report a single-step, Au-based, lateral-flow immunoassay strip assay for the simultaneous detection of triazophos and carbofuran. Most of the pesticides are inhibitors of an enzyme acetylcholinesterase (AChE), which is crucial to human health. This enzymatic reaction can be utilized to make biosensors; for example, the concentration of a pesticide was measured using a localized surface plasmon resonance fiber-optic biosensor, which monitors AChE inhibition (Guo et al., 2009). The enzyme was immobilized on the surface of AuNPs and alters the light on inhibition with a pesticide (e.g., paraoxon) that enables its quantification.

NPs for Plant Pathogen Detection

NMs can be applied as a rapid diagnostic tool or a biomarker against various plant pathogens and can be used either directly or indirectly for pathogen detection or used as an indicator for detecting specific diseases. AuNP-based immunosensors were utilized for detecting Karnal bunt (Tilletia indica) disease in wheat using surface plasmon resonance (Singh et al., 2010). Fluorescence SiNPs, combined with Ab, were utilized to detect Xanthomonas axonopodis pv. vesicatoria, known to cause bacterial spot disease in Solanaceae plants (Yao et al., 2009).
NP-Based Smart Plant Sensing System

The smart plant sensing system offers precise management of costly agrochemicals (i.e., pesticides, fertilizer, nutrients, and water) and mitigates major plant stress events in a changing climate. Increasing total crop yield requires innovative and high-throughput smart plant sensing approaches for developing plant stress-tolerance varieties and increasing the use of limited resources, such as nutrients and water. The smart nano sensors used for the optimization of crop growth and precisely detecting stress and limited resources can communicate through wireless and optical signals for real-time monitoring of plant health status (Giraldo et al., 2019). Regular monitoring of the health status of plants and possible occurrence of any disease must be done with the help of Raman and infrared spectroscopy that generate low signal-to-noise ratios and involve complicated and costly equipment (Wilson et al., 2015; Altangerel et al., 2017). Recently, remote sensing tools have improved the signal-to-noise ratio for monitoring individual plant health status and can directly communicate with hyperspectral imaging cameras and smartphones with a nanobiotechnology-based smart plant sensing system (Baret et al., 2007; Hatfield et al., 2008; Woffert et al., 2017; Padilla et al., 2018).

Real-time monitoring of plant resource deficits or stressors is based on crucial signaling molecules (i.e., calcium, ROS, NO, glucose, and sucrose) and plant hormones (i.e., ABA, ethylene, jasmonic acid, and methyl salicylate) by a nanotechnology-based smart sensing system (Kim et al., 2010; Gilroy et al., 2014; Giraldo et al., 2019). NMs, having unique surface chemistry, electrical and thermal characteristics, enhanced sensitivities, and enhanced detection limits, are suitable for better sensing systems for crucial signaling molecules in vivo (Yao et al., 2014). These emerging properties of NMs make them fluorescent in low or transparent-background windows and ultra-low photobleaching of living tissue and allow the detection of analytes with high spatiotemporal resolution down to the single-molecule level and millisecond time scales (Guo et al., 2014; Hong et al., 2015).

QDs are fluorescent NM sensors used for highly glucose selective (500–1,000 μM) emission ranges from the visible to the near-infrared (nIR) for assessing plant productivity and stress (Li J. et al., 2018). Short-lived signaling molecules, such as calcium, ROS, NO, glucose, and nitroaromatics, can be real-time monitored, applying SWCNT sensors in the selected region of the leaf that can reported fluorescence intensity with high spatiotemporal resolution (seconds) (Giraldo et al., 2014, 2015; Wong et al., 2017). Analytes bind with the SWCNT sensor humic phase coating, both altering the nIR fluorescence intensity or shifting wavelength. A variable concentration of an analyte present in cells, subcellular space, and the whole plant, for example, calcium and ROS, results in fast spatiotemporal pattern changes in waves with time and subcellular locations (Zhang et al., 2013; Kruss et al., 2014). Integration of different simulations, mainly diffusion and stochastic kinetic, helps to elucidate the complex data with a productive relationship under different resource deficiency and stress conditions. In the future, system biology integration of extensive biological data (affinities, the rate constant, sensitivity, selectivity, and dynamic range) via computational modeling that offers translation of plant chemical signaling into digital information is important for decision and action of agriculture devices.

In the past decades, wearable sensors have been developed through nanotechnological innovation for human clothing and skin application (Heikenfeld et al., 2018). Therefore, it opens a new window that offers wearable nanoelectronic circuits on plant surfaces for wireless communication of volatile compounds with low concentration in real-time. SWCNT channels and graphic electrodes transferred onto leaf surfaces of live plants can sense trace levels of a gaseous compound down to 5 ppm concentration (Lee et al., 2014). Binding of SWCNT-based sensors equipped with copper complexes to ethylene gas emitted from plant fruits leads to changes in the resistance proportional to the volatile compound concentration (Esser et al., 2012). CNT-based sensors are now available in the market for detection of ethylene, which is a plant hormone and crucial indicator of fruit ripening. Furthermore, plants embedded with functionalized SWCNTs with bombolitin peptide are used for real-time monitoring of explosive nitroaromatics (i.e., picric acid) in a smartphone or laboratory-grade camera for changes in nIR fluorescence intensity (Wong et al., 2017). Similarly, green fluorescent protein-based calcium sensors act as a detector for plant stress.

Nanobiotechnology-based sensors have the capacity for real-time monitoring of chemical signaling by phenotyping or agricultural devices embedded with smartphone, meteorological station, or hyperspectral imaging cameras to alleviate the environmental stress and selection of high yielder plant traits, for example, detection of ZnO and cerium oxide NPs to protect the plant from heat and salinity (increasing potassium retention in leaf mesophyll) by scavenging reactive oxygen (Graham et al., 2016; Wu et al., 2017b, 2018). Similarly, CuO can protect from fungal root disease in watermelon (Citrullus lanatus), and nanocrystals reduce cold damage (Alhamid et al., 2018; Borgatta et al., 2018).

Smart plant sensors still need testing in agriculture field conditions, such as environmental condition, plant growth,
and how development can affect their performance. The communication of plant sensors with electronic devices is still limited to controlled laboratory conditions. If the field trials are fruitful, the sensor can provide real-time information regarding the requirement of nutrients, water, pesticides, and fertilizer for specific needs.

**NPs FOR MANAGING THE AGRICULTURAL POST-HARVEST WASTE**

Most of the recent literature on the application of nanotechnology emphasizes nano pesticides, nano fertilizers, nanosensors, and crop protection. The abundant amount of lignocellulose has been obtained from agricultural waste that can be utilized efficiently to prepare functional NMs, such as nanocellulose (Shahabi-Ghahafarrokhi et al., 2015), nanocomposites (Othman, 2014), and biochar. Rice and wheat husks can be used to produce value-added products that alleviate concerns about disposing of agricultural waste (Kaur et al., 2016). By utilizing electrospinning, waste cotton fibers and cellulose can be converted into value-added products (Ramakrishna et al., 2006). Cellulose is the most abundant biopolymer that makes the backbone of tree trunks and branches. It is also considered the main component of the paper industry. It can be efficiently utilized for the production and application of nanocellulose and natural fiber (Dai and Fan, 2013; Figure 3). Nanoscale cellulosic materials are very hydrophilic, called aerogels, that offer a wide range of applications. Their properties are very distinct from their bulk parts. Holocellulose aerogels can be widely utilized as adsorption materials owing to the nano-fibrillar structure with high surface area and high adsorbing properties (Muñoz-García et al., 2015). Silica, an inorganic element, can be extracted from the rice husk, which is known for its excellent source of nano and microsilica. The effective use of nano-silica conjugated with validamycin is for the controlled delivery of water-soluble pesticide (Liu F. et al., 2006). Nano silica conjugated with methyl methoxy silane was suggested as a plant growth regulator and nanofungicide against mildew disease (Huang et al., 2015). Some of the nano pesticides are already hitting the market (Table 4), but their relation to the controlled release of agrochemicals is still ongoing and may take several years. We reviewed the detailed information for NP-based companies’ related products and properties (for more detail refer to Table 4).

**TOXICOLOGICAL IMPACT OF NP RISK AND HEALTH HAZARDS IN AGRICULTURE APPLICATION**

Despite huge research, limited progress has been made in understanding the NM risk and health hazards. NP application in agri-food industries majorly lacks the transparent and precise framework for risk governance across the different sectors (Figure 1D). The development of harmonized regulatory frameworks in the field of nanosafety has been focused on safety-by-design synthesis approaches (Kraegeloh et al., 2018; Stone et al., 2018). To share the information among different nanotechnology, fields are required not only to show nanosafety research advancement, But also risk assessment, risk management, policymaking, and to support risk communication among the different stakeholders (for example, society, industries, researchers, policymakers, insurance companies, and the general public). Mostly, nanosafety researchers work with a two-way approach (Bos et al., 2015). The first approach is to understand human health toxicity, which is predominately targeted to organisms, tissues, and cells (for example, mouse skin and immune cells). Second is environmental health risk; communities are primarily concerned with other branches of the tree of life (for example, single-cell organisms, plant tissues, invertebrates, and fish). Subsequently, plant-based nanosafety research has been focused on the intentional or direct exposure of food crops to specific NMs (for example, nano pesticides, nano fertilizer, and nanoherbicides), indirect or unintentional exposure (i.e., spray drifting, leaching, and runoff of NPs; Figure 5).

The primary point that needs to be addressed before exploiting NPs in any field is their physiochemical properties as this could have a direct impact on their potential health and environmental hazards that somehow limit their actual potential as a beneficial entity. Of these characteristics, size and concentration are the foremost properties of the NPs important from the toxicology perspective (Table 5). It can be correlated with the increased surface area with a decreased size that ultimately leads to higher uptake and interaction with the plant system, thus increasing the chances of generating adverse effects (Nel et al., 2006). It has been extensively reviewed by Ma et al. (2010) that NPs of size <5 nm can readily be translocated through cell wall pores and 20 nm through plasmodesmata; thus, it can be perceived that NPs with lower size range can be quickly taken up by the plants and could cause more phytotoxicity even at lower concentrations (Ma et al., 2010; Rico et al., 2011; Wang et al., 2013). As in the case of larger size graphene oxide (GO), the potential translocation from roots to shoots is hindered, thus lowering the bioaccumulation (Chen et al., 2017).

It is worth mentioning here that the concentration-dependent effects also mark the critical evidence of NP benefits or toxicity. For instance, ZnO NPs and CeO$_2$ NPs show its toxic effects, such as reduced yield (31.6%), when supplied in higher concentrations (800 mg/kg) and not at lower concentrations (400 mg/kg) in cucumber plants (Zhao et al., 2013b). On the contrary, ZnO NPs promote seed germination and seedling vigor in addition to increased chlorophyll content when supplied in 1,000 ppm concentration to peanut plants (Prasad et al., 2012). The main mechanism of NPs toxicity is more specifically metal NPs relying on the formation of excessive ROS, particularly by shredding ions in the biological environment, thus creating toxic effects (Yan and Chen, 2019). It also interferes with the electron transport chain of mitochondria and chloroplast. Different stress factors also affect the carbon fixation that, in turn, causes photoinhibition and, ultimately, more production of superoxide anion radicals and H$_2$O$_2$ (Foyer and Noctor, 2005). The resulting overproduced ROS further interacts with the cellular components, causing protein modifications, lipid peroxidation, and damage to DNA (Møller...
| S.No | Company | Nanomaterial | Name of product | Properties | Application | Country |
|------|---------|--------------|----------------|------------|-------------|---------|
| 1.   | Aqua-Yield Hub | Potassium (Nanocapsule) | NanoK™ | • Crop Yield Enhancement  
• Potassium delivery to crops | Nano fertilizer | USA |
| 2.   |  | Zinc (Nanocapsule) | NanoZn™ | • Plant Growth Regulation  
• Zinc delivery to crops | Nano fertilizer | USA |
| 3.   |  | Combined | NanoRise™ | • Plant Growth Regulation  
• Plant Growth Regulation  
• Crop Yield Enhancement | Nano fertilizer | USA |
| 4.   |  |  | NanoPro™ | • Plant Growth Regulation  
• Pesticide uptake enhancement and efficacy | Nano fertilizer | USA |
| 5.   | Silvertech Kimya  
Sanayi ve Ticaret Ltd. | Zinc oxide  
Titanium dioxide | NANO FERTILIZERS | • Plant Growth Acceleration  
• Crop Yield Enhancement  
• Photosynthesis Improvement  
• Root Activity Improvement  
• Growth Promoter Harvest enhancement  
• Soil salinization resistant | Nano fertilizer | TURKEY |
| 6.   | Land Green &  
Technology Co | Mn, Cu, Fe, Zn, Mo, N | NovaLand-F | • Preventing the growth of algae  
• Plant Growth Regulation  
• Plant Growth Acceleration  
• Increased resistance to plant diseases  
• Plant Metabolism Acceleration | Nano fertilizer | TAIWAN |
| 7.   |  |  | NovaLand Nano—Mn, Cu, Fe,  
Zn, Mo, N | • Head-heavy Balance  
• Plant Growth Regulation  
• Plant Growth Acceleration  
• Photosynthesis Improvement  
• Root Activity Improvement  
• Root Vigor Improvement Active  
• Growth Promoter Harvest enhancement  
• Soil salinization resistant | Nano fertilizer | TAIWAN |
| 8.   | Bio Nano Technology | NA | HYPER FEED 19-19-19 | • Nutritional  
• Antimicrobial Activity  
• Non-toxic Environmentally Friendly  
• Antifungal Activity Plant Growth  
• Regulation Nutritional Plant Growth Acceleration | Nano fertilizer | EGYPT |
| 9.   | NANOPAC (M) Sdn Bhd | NA | Nano fertilizer | • Nutritional  
• Antimicrobial Activity  
• Non-toxic Environmentally Friendly  
• Antifungal Activity Plant Growth  
• Regulation Nutritional Plant Growth Acceleration | Nano fertilizer | MALAYSIA |
| 10.  | Microwell Bio Solutions Sdn Bhd | Potassium | Groagro 4: Super Kalium Catalyst + T.E | • Nutritional Value improvement  
• Plant Growth Acceleration | Nano fertilizer | MALAYSIA |
| 11.  |  | Potassium | Groagro 1: Super Nano-Catalyst Kalium + T.E | • Nutritional Value improvement  
• Plant Growth Acceleration | Nano fertilizer | MALAYSIA |
| 12.  | SHEPROS SDN. BHD. | NA | NANOSORB FERTILIZER BOOSTER | • Plant Growth Regulation  
• Nutritional Value improvement  
• Plant Growth Acceleration  
• Strengthening the supply of plant micronutrients iron and zinc and manganese  
• Plant Metabolism Acceleration | Nano fertilizer | MALAYSIA |
| 12.  | Bioteksa | Iron (Nanoparticle /Nanopowder)  
Magnesium (Nanocapsule) | NUBIOTEX® HYPER Fe+Mg | • Plant Growth Regulation  
• Nutritional Plant Growth Acceleration  
• Plant Resistance Enhancement | Nano fertilizer | Mexico |

(Continued)
| S.No | Company | Nanomaterial | Name of product | Properties | Application | Country |
|------|---------|--------------|----------------|------------|-------------|---------|
| 13.  | Calcium (Nanoparticle /Nanopowder) | NUBIOTEK® ULTRA Ca | • Plant Growth Regulation  
• Nutritional Plant Growth Acceleration | Nano fertilizer | Mexico |
| 14.  | HPL Agronegocios | Magnesium (Nanocapsule) | FERTIL CALMAG | • Plant Growth Regulation  
• Absorption Enhancement | Nano fertilizer | Brazil |
| 15.  | Laboratorios Bio-Médicin | Manganese (Nanocapsule)  
Molybdenum (Nanocapsule) | Nanovec TSS 80 | • Agriculture Seed treatment | Nano fertilizer | Brazil |
| 16.  | HPL Agronegocios | Calcium Nanoparticle /Nanopowder | FERTILE CALCIUM 25 | • Nutritional Absorption Enhancement | Nano fertilizer | Brazil |
| 17.  | Litho Plant | Calcium Nanoparticle /Nanopowder  
Manganese Nanoparticle /Nanopowder | Lithocal | • Nutritional Absorption Enhancement | Nano fertilizer | Brazil |
| 18.  | Samarita | Phosphorous (Nanoparticle /Nanopowder)  
Diameter : 2 nm  
Potassium (Nanoparticle /Nanopowder)  
Diameter : 2 nm | NANOPOWER CaMag | • Plant Growth Acceleration  
• Crop Yield Enhancement | Nanofertilizer | Brazil |
| 19.  | Kimitec Group | Phosphorous (Nanoparticle /Nanopowder)  
Diameter : 2 nm  
Potassium (Nanoparticle /Nanopowder)  
Diameter : 2 nm | FOSVIT K30 | • Self-defense enhancement | Nano fertilizer | Spain |
| 20.  | Tropical Agrosystem India (P) Ltd. | ZINC | TAG NANO ZINC | • Plant Growth Regulation  
• Photosynthesis Improvement  
• Root Activity Improvement | Nano fertilizer | India |
| 21.  | Calcium | TAG NANO CAL | • Plant Growth Regulation  
• Photosynthesis Improvement  
• Root Activity Improvement | Nano fertilizer | India |
| 22.  | POTTASH | TAG NANO POTASH | • Plant Growth Regulation  
• Photosynthesis Improvement  
• Root Activity Improvement | Nano fertilizer | India |
| 23.  | Alert Biotech | Zinc (Nanoparticle /Nanopowder)  
Zinc (Chelated) | Nano Zinc (Chelated) | • PH stability  
• Nutritional | Nano fertilizer | India |
| 24.  | Boron (Nanoparticle /Nanopowder) | Nano Bor 20% | • PH stability  
• Nutritional | Nano fertilizer | India |
| 25.  | Zinc (Nanoparticle /Nanopowder) | Nano Zinc (Soil Application 21%) | • PH stability  
• Nutritional | Nano fertilizer | India |
| 26.  | Nano Agro Science Co-operative Society Ltd. | Phosphorous (Nanoparticle /Nanopowder) | NASCO Escort-P | • Environmentally Friendly  
• Organic Root Activity Improvement  
• Root Vigor Improvement | Nano fertilizer | India |
| 27.  | Phosphorous (Nanoparticle /Nanopowder) | NASCO Escort-P | • Environmentally Friendly  
• Organic Root Activity Improvement  
• Root Vigor Improvement | Nano fertilizer | India |
TABLE 5 | Detailed information on the toxicity of NP-based agrochemicals with various concentrations, size, and plant species tested.

| S.No | Nanoparticles | Concentration | Size | Plant species | Effects | References |
|------|---------------|---------------|------|---------------|---------|------------|
| 1.   | Fe$_2$O$_4$   | 30, 100, and 500 mg/L | Lollum perenne L. and Cucurbita mixta cv. white cushion | Oxidative stress, increased superoxide dismutase and catalase enzyme activities, lipid peroxidation | Wang et al., 2011 |
| 2.   | Citrate coated-Ag and ZnO | 200 and 1,000 µg/mL, respectively | 56.1 and 17.4 nm, respectively | Zea mays L. and Brassica oleracea var. capitata L. | Alterations in cellular structures, Tunneling effect with nZnO, metaxylem count changes by citrate coated Ag | Pokhrel and Dubey, 2013 |
| 3.   | Ag           | 20, 51, and 73 nm | 100 mg/L | Vicia faba | Altered PSII activity, stomatal conductance, and CO$_2$ assimilation, Inhibits root elongation at highest concentration (250 and 500 mg/L), effects on shoot elongation were less severe | Falco et al., 2020 |
| 4.   | ZnO          | 5, 10, 25, 50, 75, 100, 125, 250, and 500 mg/L | Brassica napus | Increased APX and SOD activity levels, and lipid peroxidation in roots through generation of H$_2$O$_2$, altered contents of non-enzymatic antioxidants, total phenols, flavonoids, -carotene, and lycopene in fruits were significantly reduced | Mousavi Kouhi et al., 2014 |
| 5.   | ZnO          | 300, 600, and 1,000 mg/kg | <100 nm | Solanum lycopersicum | Plant species-dependent effects were observed, differential phytotoxicity depending on the nanoparticles type, significant changes in seed germination but no acute toxicity, lettuce, onion, ryegrass, tomato were shown effective for both the nanoparticles | Akanbi-Gada et al., 2019 |
| 6.   | TiO$_2$ and CeO | 0, 250, 500, and 1,000 µg/mL | 130-295 nm; TiO$_2$, 230-290 nm; CeO | Lactuca sativa, Lycopersicon lycopersicum, Brassica oleracea, Glycine max, Daucus carota, Lollum perenne, Z. mays, Cucumis sativus, Avena sativa, and Allium cepa | Increased APX and SOD activity levels, and lipid peroxidation in roots through generation of H$_2$O$_2$, altered contents of non-enzymatic antioxidants, total phenols, flavonoids, -carotene, and lycopene in fruits were significantly reduced | Andersen et al., 2016 |
| 7.   | CuO and Al$_2$O$_3$ | 0, 20, 200, and 2,000 µg/mL | 18 nm; CuO and 21 nm; Al$_2$O$_3$ | Solanum lycopersicon | Plant species-dependent effects were observed, differential phytotoxicity depending on the nanoparticles type, significant changes in seed germination but no acute toxicity, lettuce, onion, ryegrass, tomato were shown effective for both the nanoparticles | Ahmed et al., 2018 |
| 8.   | CuO          | 0, 50, 100, 200, and 500 mg/kg | Glycine max cv. Kowsar | ROS-mediated membrane damage and membrane lipid peroxidation is observed along with activity of antioxidant enzymes, DNA conformation by NPs is affected by both intercalative and non-intercalative modes, Al$_2$O$_3$-NPs induced lesser change in TrnDNA conformation Macromolecular change in amide-I and II of proteins and carbohydrates, CuO with more toxicity than Al$_2$O$_3$, concentration dependent decrease in fresh and dry biomass | Yusefi-Tanha et al., 2020 |
| 9.   | TiO$_2$ and ZnO | 0, 5, 10, 20, 40, and 80 mg/kg | ~30 nm | Hordeum vulgare L. | The antioxidant enzyme activities are diversely affected but no changes in seed germination and root elongation has been observed, ZnO was more toxic than TiO$_2$ | Dogaroglu and Kåell, 2017 |
| 10.  | CuO          | 10, 50, 100, and 500 mg/L | Brassica oleracea var. botrytis and Solanum lycopersicum | 100 and 500 mg L$^{-1}$ of CuO NPs has resulted in reduction of total chlorophyll and sugar content, augmented lipid peroxidation, electrolyte leakage, and antioxidant enzyme activity, concentration dependent increase in superoxide and hydrogen peroxide formation in leaves, deposition of lignin in roots seen at higher concentration | Singh et al., 2017 |

(Continued)
### TABLE 5 | Continued

| S.No | Nanoparticles | Concentration | Size       | Plant species                | Effects                                                                                     | References          |
|------|---------------|---------------|------------|------------------------------|--------------------------------------------------------------------------------------------|---------------------|
| 11.  | CuO           | 10 g/L        | 30–50 nm   | *Hordeum sativum distichum*  | Ultrastructural changes in chloroplast, vacuoles, mitochondria and stomata, impaired germination rate, root morphology, cell wall, epidermis, cortical layers and vascular bundles, Inhibits root, and shoot length | Rajput et al., 2018 |
| 12.  | FeO           | 30, 40, or 50 mg/L | 12 nm   | *Lemma minor*                | The chlorophyll content decreased at high iron oxide NP concentrations, which disrupted the light absorption mechanism, ROS production, diminishes photosynthetic pigments or chl a/chl b content ratio | Souza et al., 2019  |
| 13.  | TiO$_2$, ZnO, Al$_2$O$_3$, and CuO | 0.05, 0.5, 2, and 5 mg/ml | 148–248 nm | *Raphanus sativus, Cucumis sativus, Solanum lycopersicon, and Medicago sativa* | Stimulates metallothionein production, inhibited relative seed germination, root/shoot tolerance index however differential effects were observed based upon the plant species and nanoparticles type | Ahmed et al., 2019  |
| 14.  | CuO, TiO$_2$, and Fe$_2$O$_3$ |               |            | *Triticum aestivum*         | Decreased contents of Fe and Zn by CuO treatment and reduced human essential amino acids, overall increased amino acid concentration by TiO$_2$, | Wang et al., 2019   |
| 15.  | CuO, ZnO, and NiO | 100, 250, 500, and 1,000 mg/L | 25–55 nm; CuO, 18 nm; ZnO, 10–20 nm; NiO | *Abelmoschus esculentus* | Suppressed plant growth in a concentration-dependent manner, reduced shoot and root length, decreased chlorophyll content, significantly altered total phenolic and total flavonoid contents, enhanced ROS, and malondialdehyde production | Baskar et al., 2020 |
| 16.  | Se            | 0, 0.5, 1, 10, and 30 mg/L | 20 nm   | *Capsicum annuum*            | Impose epigenetic changes, upregulated bZIP1 and WRKY1 transcription factors, altered growth metabolism and anatomy of plant, caused DNA hyper-methylations | Sotoodehnia-Korani et al., 2020 |
| 17.  | Se            | 0, 1, 4, 10, 30, and 50 mg/L | 10–30 nm | *Momordica charantia*        | More concentrations cause stem bending, impaired root meristem, and severe toxicity, cause variation in DNA cytosine methylation, reflecting the epigenetic modification, also stimulates activities of catalase and peroxidases, disrupts xylem conducting tissues | Rajaee Beibahani et al., 2020 |
| 18.  | CeO$_2$       | 0, 50, 100, and 1,000 mg/L | <25 nm   | *Lactuca sativa*             | Higher concentration treatment significantly deteriorate plant growth and biomass production, Superoxide dismutase, Peroxidase, Malondialdehyde activity was disrupted | Gui et al., 2015    |

### TOXICITIES OF NANOTUBES (NT)

| S.No | Nanoparticles | Concentration | Size                                                                 | Plant species | Effects                                                                                     | References          |
|------|---------------|---------------|----------------------------------------------------------------------|---------------|--------------------------------------------------------------------------------------------|---------------------|
| 19.  | MWCNT and SWCNT | 1 and 10 mg/kg | 1–4 nm outer diameter and 5–30 µm length; SWCNT-OH, 30–50 nm outer diameter and 0.5–2.0 µm length; MWCNT-COOH | *Solanum lycopersicum* | Delay in early growth and flowering, MWCNT effects were seen on first fruit, SWCNT has effects on physiology, such as increased salicylic acid | Jordan et al., 2020  |
| 20.  | Hollow MWCNT, Fe-filled carbon, and Fe-Co-filled carbon NT | 0, 10, 50, and 300 mg/L | 5 nm thickness                                                                 | *Oryza sativa L.* | Inhibited rice growth, decreased concentrations of endogenous plant hormones, decreased nitrogen assimilation | Hao et al., 2016    |
| 21.  | MWCNT         | 0, 125, 250, 500, and 1,000 µg/mL | Outer diameter 5–15 nm and length 50 µm | *Cucurbita pepo L.* | Toxicity effects on germination rates or slow germination of seeds, enhanced cellular injuries, inactivated antioxidant enzymes | Hatami, 2017        |
| 22.  | MWCNT-COOH    | 0, 25, 50, and 100 mg/L |                                                                 | *Ocimum basilicum* | High dosage (100 mg L$^{-1}$) of MWCNT-COOH leads to toxicity effects | Gohari et al., 2020  |

The summary of the results is also provided with specific reference citations.
et al., 2007, Huang et al., 2019, Wang et al., 2020). It also has positive implications as it helps in mitigating stress-related issues in plants that show the importance of equilibrium between ROS production and scavenging (Sharma et al., 2012). The increased ROS has substantial implications on the activity of antioxidative enzymes (also shown in Table 5) in plants under NP stress (Faisal et al., 2013; Jiang et al., 2014; da Costa and Sharma, 2016).

Recent reports have also shown that phytohormones play an essential role under external insult response signaling. The NPs cause a decrease in the auxins, cytokinins, and salicylic acid, suggesting hormone imbalance in plants, thus affecting overall metabolism (O’Brien and Benková, 2013; Vankova et al., 2017). A very high concentration of NPs may severely affect photosynthesis, which may result in plant growth suppression or plant death. Several reports have observed significant decrease or inhibition in plant growth as the result of NP exposure (for more detail refer to Table 5).

In light of the reports mentioned above, it can be perceived that several factors come into the picture that have to be considered before realizing the positive utilization of NPs in the agricultural system. Plant–soil interaction is the main driving force for agricultural production; thus, it is critical to study the physicochemical characteristics of the soil system. It is considered to be the paramount sink for the NPs, and hence, their interaction with the soil components could impose a profound impact on the fate of NPs. It has been observed that pH, organic content, and cation exchange capacity results in an increased risk of toxicity (Servin and White, 2016). For instance, loamy clay soil with pH 5.5 reported no toxicity by ZnO NPs even at a concentration of 2,000 mg/kg, whereas, loamy clay soil with pH 7.36 observed noticeable toxicity at a concentration of 45.45 mg/kg (Du et al., 2011). In addition to this, the soil organic matter also plays a significant role in changing the safety issues of the NPs as evident from reduced toxicity of the ZnO NPs when provided with Alginate at a concentration of 400–800 mg/kg. However, ZnO NPs alone cause a significant reduction in plant biomass (Zhao et al., 2013a). NPs also have a direct impact on the soil microbial community structure in a dose-dependent manner as observed by using DNA fingerprinting analysis that showed declining taxa of Rhizobiales, Bradyrhizobiaceae, and Bradyrhizobium (nitrogen fixation process); however, positive effects were also envisaged on Sphingomonadaceae and Streptomycetaceae. It is interesting to note here that NPs are declining the taxa related to nitrogen fixation while increasing the taxa of the community associated with the decomposition process of organic pollutants and biopolymers (Ge et al., 2012). Furthermore, AgNPs showed a dose-dependent impact on the nitrate-reduction activity of Rhizobium and Azotobacter with a 0.2 ppm increase in the activity in Azotobacter (Shahrokh et al., 2014). Environmentally based nanosafety research has primarily targeted accidental environmental releases of NPs during the manufacturing, use, and disposal of nanoforumlized agriculture nanoproducts. Mukherjee et al. (2016) studied the comparative toxicity of NPs Al₂O₃ at ZnO (15 nm), ZnO at KH₅PO₄ (20 nm), and bare-ZnO (10 nm) to grown green peas (Pisum sativum L.) (Figure 5). Plants treated with Al₂O₃ at ZnO NP (1,000 mg/kg for 65 days) had higher Zn level in seeds and roots relative to bulk and the other Zn NP exposure. Photosynthetic pigments (Chl-a and
carotenoid) significantly increased, but the carbohydrate and protein content remained largely unaffected across all treatments except $\text{Al}_2\text{O}_3$ at ZnO NP. In correspondence, a very high concentration of ZnO NPs (1,000 mg/L) did not significantly alter root elongation and seed germination. In contrast, Cu and Ag-NPs inhibited root growth of zucchini (Cucurbita pepo). The exposure of AgNPs at a concentration of 500 and 100 mg/L resulted in 57% and 41% drastic reduction in plant biomass and transpiration rate, respectively (Stampoulis et al., 2009).

Wang et al. investigated the impact of 200 and 300 (mg/L) ZnO NP exposure, which decreased Arabidopsis growth by ~20 and 80%, respectively, relative to the control. The results show a decrease in the expression of chlorophyll synthesis genes and photosystem structure genes. In contrast, an increase in the expression of carotenoid synthesis genes may contribute to reducing the photosynthesis efficiency linked to overall phytotoxicity in the plants. Asli and Neumann (2009) report that colloidal suspensions of TiO$_2$-NPs (30 nm) accumulated in the root at the cell wall surfaces and decreased cell wall pore size from 6.6 nm to about 3 nm, affecting water transport capacity and, therefore, transpiration of intake plants (Zea mays L.). Genotoxic and phytotoxic impact of CeO$_2$ and TiO$_2$ NP suspensions were investigated on the early growth of barley with concentrations of 0, 500, 1,000, and 2,000 mg/L for 7 days (Mattiello et al., 2015). Genotoxicity [randomly amplified polymorphism DNA (RAPDs) and mitotic index] observed changes in RAPD banding patterns and the chromosomal level with decreasing cell divisions in treated root tip cells compared to control plants. ROS generation and ATP content increased at the concentration of 500 mg/L in both root and shoot (Figure 1D). Authors also observed the presence of CeO$_2$ and TiO$_2$ NPs in exposed root cells through ICP-OES and TEM EDSX microanalysis.

Indeed, theoretically, there may be the direct release of NMs into the environment from agro-nanotechnologies and incorporation into the human exposure pathway through the food chain. The existing challenges facing agricultural nano chemical application are due to the potential migration of NMs through the food chain, so safety assessment is urgently required. There are various modes of exposure of nanoagrochemicals to humans, such as growing demand for food crops (for example, population growth and increasing demand for animal-based products), large food product waste in affluent industries, and other agriculture activities (pre- and post-harvesting of food crops) (Figure 5). In addition, plants present a significant opportunity to facilitate the transfer of NPs to the different trophic levels and ultimately to the food web as they are largely consumed by the lower trophic-level organisms, animals, and people.

It is important to understand the one health concept, especially in the context of agriculture nanotechnology. One cannot minimize the previous research or reports focusing on the need for viewing of modern challenges to health through a one health concept; this cannot be underestimated. Also, many peer-reviewed articles frame their research finding as an example of the demand for a one health approach. We must also appreciate the excellent effort of various international organizations (World Health Organization, the World Organization for Animal Health, and the Food and Agriculture Organization of the United Nations) devoted to promoting the one health concept and spreading the awareness of their importance (Lombi et al., 2019).

Here, we propose a transdisciplinary and holistic approach that underpins the one health concept and is crucial for sustainable development and policy implementation of nanotechnology (Figure 5). We are living in an interdependent ecosystem wherein all the organisms on the planet, including humans, animals, plants, and associated microbiota, stay together for their existence by mutual interaction. In particular, the overuse and inappropriate practices of agrochemicals as growth promoters of food crops significantly increase the migration of NMs in the food chain. The nanotoxicity and associated human health hazards require an intelligent testing strategy framework for risk evaluation of agro-nanotechnologies. Along with preliminary assessment (document) of the existing knowledge and the gaps, they categorize and integrate data to develop an intelligent approach to grouping NMs based their properties (for example, particle size, charge, molecular weight, solubility, and composition) and their biological impacts in order to intelligently design next-generation risk-assessment strategies and safety to the risks emerging from this technology.

**FUTURE PERSPECTIVE**

Nanotechnology strikes at an indispensable part of numerous domains of the food industry without any doubt. It has promising applications; however, it cannot be overlooked that most of the knowledge we gathered about it is mainly from laboratory experiments. It is almost uncertain about apprehending the practical application while not understanding its impact on environment-related toxicity. Furthermore, not having the guidelines, regulatory bodies, and similar organizations creates obstructions for the selling of novel NP-based agrochemicals. Hence, there is a requirement to execute large trials in forwarding and developing futuristic investigations based on perceived gaps of knowledge. In this setting, we propose six critically important fundamental features:

1. The open government awareness program to educate the common people about food nanotechnology and its applications through formulating an adequate database and proof to assist as logistic support of both the public and food manufacturers.
2. The comprehensive examination of future studies must be featured to determine the risk associated with the usage of NP-based products in the agricultural sector to make a more practical strategy.
3. To identify the minimum concentration dose utilizing the concentration-dependent study in the natural soil system for the NP, which would be non-toxic and can be useful in field applications.
4. To gain a comprehensive understanding of the bioaccumulation capability of NPs during field applications and its effect on nanotoxicity and further knowledge of tropic chain transfer in the ecosystem chain and deciphering the sufficient safety estimate.
5. Broad understanding of soil physico-chemical interaction with NPs for reducing danger toward not distorting the soil microbiota. Further determination of the rotation of soil for
modifying the destiny, carrier, and bioavailability of NPs to diminish their following toxicity and their trustworthy and useful utilization in agriculture.

6. Last, we strongly suggest the substitution of synthetic NPs to biosynthesized and performing in-depth research. In this way, utilizing the environmentally friendly protocol may hold comparatively minor or no toxicity, and henceforth, future studies must specifically concentrate on their functional efficiency. In addition, pilot studies must be set in natural conditions (growing plants in soil) to give an explicit depiction of the environmental influence of NPs.

In Addition, Some Safety Measures Should Be Considered

1. It is crucial to harmonize the frameworks of nanosafety regulations focusing on safety-by-design synthesis approaches so that it should not be overused at the toxic level.

2. The physiochemical properties of any new NP-based agrochemical should be analyzed substantially in long-term experiments before exploitation in any field work as it could have a direct impact on health and environmental hazard that will limit the actual potential as a beneficial entity.

3. Environmentally based nanosafety research has to be primarily targeted to study the accidental environmental releases of NPs during the manufacturing, use, and disposal of nanoformulized agriculture nanoproducts.

CONCLUSION

The present review highlights the different roles of NPs in the agriculture and livestock industry. The implementation of nanotechnology in modern agriculture helps in uplifting the global economy by providing support and advances in different ways. Considering different challenges posed by the increasing population, plant diseases, animal diseases, and climate change, the introduction of NPs significantly contributes to addressing these pressing issues, expanding the use of conventional pesticides and fertilizers to enhance crop production, ultimately causing harm to the natural environment. With the advent of NPs the effectiveness and agronomic efficiency are highly improved compared to traditional resources. The better use of pesticides encapsulated in different nanoformulations provides their better application, and controlled release protects the environment. Several nano pesticides and nano fertilizers are under development, and a few of them are already marketed. The study of NP-plant interaction is an important point to consider to understand the physiological and biochemical responses imposed by plants. Emerging techniques are developed to locate and quantify NPs through the plant system that gives the idea of their transformation and safety aspects in a complex system. Nanotechnology exploits the unique property of NPs and develops nanosensors to detect pesticide residue and various soil parameters, such as pH and moisture.

CONSENT FOR PUBLICATION

The authors gave their consent for publication of the research results.

AUTHOR CONTRIBUTIONS

DM, GK, and SA designed and wrote the manuscript. DM, GK, PS, KY, and SA revised and finalized the draft. SA supervised the whole project and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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REFERENCES

Abdel Latef, A. A. H., Srivastava, A. K., El-sadek, M. S. A., Kordrostami, M., and Tran, L. S. P. (2018). Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions. Land. Degrad. Develop. 29, 1065–1073. doi: 10.1002/ldr.2780

Abou-Zeid, H., and Ismail, G. (2018). The role of priming with biosynthesized silver nanoparticles in the response of Triticum aestivum L to salt stress. Egypt. J. Bot. 58, 73–85. doi: 10.21608/ebj.2017.1873.1128

Acharya, P., Jayaprakash, G. K., Crosby, K. M., Ilion, J. L., and Patil, B. S. (2020). The role of priming with biosynthesized silver nanoparticles in the response of Triticum aestivum L to salt stress. Egypt. J. Bot. 58, 73–85. doi: 10.21608/ebj.2017.1873.1128

Aghdam, M. T., Mohammadi, H., and Ghorbanpour, M. (2016). Effects of nanoparticle anatase titanium dioxide on physiological and biochemical performance of Linum usitatissimum (Linaceae) under well-watered and drought stress conditions. Braz. J. Bot. 39, 139–146. doi: 10.1007/s40415-015-0227-x

Ahmad, B., Shabbir, A., Jaleel, H., Khan, M. M. A., and Sadiq, Y. (2018). Efficacy of silicon application on wheat (Triticum aestivum) well-watered and drought stress conditions. J. Food Agric. Land. 39, 139–146. doi: 10.1007/s40415-015-0227-x

Ahmed, B., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., Ur Rehman, M. Z., et al. (2020). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere 238:124681. doi: 10.1016/j.chemosphere.2019.124681

Advices, M., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., Ur Rehman, M. Z., et al. (2020). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere 238:124681. doi: 10.1016/j.chemosphere.2019.124681

Ahmad, B., Khan, M. M. A., and Sadiq, Y. (2018). Efficacy of silicon application on wheat (Triticum aestivum) well-watered and drought stress conditions. Braz. J. Bot. 39, 139–146. doi: 10.1007/s40415-015-0227-x

Ahmad, B., Khan, M. M. A., and Sadiq, Y. (2018). Efficacy of silicon application on wheat (Triticum aestivum) well-watered and drought stress conditions. Braz. J. Bot. 39, 139–146. doi: 10.1007/s40415-015-0227-x

Ahmed, B., Khan, M. S., and Musarrat, J. (2018). Toxicity assessment of metal oxide nano-pollutants on tomato (Solanum lycopersicon): a study

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on growth dynamics and plant cell death. Environ. Poll. 240, 802–816. doi: 10.1016/j.envpol.2018.05.015
Ahmed, B., Rizvi, A., Zaidi, A., Khan, M. S., and Musarrat, J. (2019). Understanding the phyto-interaction of heavy metal oxide bulk and nanoparticles: evaluation of seed germination, growth, bioaccumulation, and metalloidion accumulation. RSC Adv. 9, 4210–4223. doi: 10.1039/C8RA09305A
Akanbi-Gada, M. A., Ogunkunle, C. O., Vishwakarma, V., Viswanathan, K., and Fatoba, P. O. (2019). Phytotoxicity of nano-zinc oxide to tomato plant (Solanum lycopersicum L.): Zn uptake, stress enzymes response and influence on non-enzymatic antioxidants in fruits. Environ. Technol. Innov. 14, 100325. doi: 10.1016/j.eti.2019.100325
Alabdallah, N. M., and Alzahrani, H. S. (2020). The potential mitigation effect of ZnO nanoparticles on [Azelmchus esculentus L. Moench] metabolism under salt stress conditions. Saudi. J. Biol. Sci. 27, 3132–3137. doi: 10.14202/sjbs.2020.08.005
Alhamid, J. O., Mo, C., Zhang, X., Wang, P., Whiting, M. D., and Zhang, Q. (2018). Cellulose nanocrystals reduce cold damage to reproductive buds in fruit crops. Biosys. Eng. 172, 124–133. doi: 10.1016/jbiosystemseng.2018.06.006
Ali, M., Kim, B., Belfield, K. D., Norman, D., Brennan, M., and Ali, G. S. (2015). Inhibition of Phytophthora parasitica and P. capsici by silver nanoparticles synthesized using aqueous extract of Artemisia absinthium. Phytopathology 105, 1183–1190. doi: 10.1094/PHYTO-01-15-0006-R
Alidoust, D., and Isoda, A. (2013). Effect of γFe2O3 nanoparticles on photosynthetic characteristic of soybean (Glycine max (L.) Merr.): foliar spray versus soil amendment. Acta Physiologiae Plantarum. 35, 3365–3375. doi: 10.1177/0373-1138-9-1369-8
Almutairi, Z. M. (2016). Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (‘Solanum lycopersicum’) L. seedlings under salt stress. Plant Omics. 9:106.
Altangerel, N., Ariunbold, G. O., Gorman, C., Alkahtani, M. H., Borrego, E. J., Anjali, C. H., Sharma, Y., Mukherjee, A., and Chandrasekaran, N. (2012). Neem (Azadirachta indica) oil nanoparticle uptake in plants: gold nanomaterial localized in roots of tomato. Environ. Sci. Technol. 46, 463–476. doi: 10.1021/es103826m
An, J., Hu, P., Li, F., Wu, H., Shen, Y., White, J. C., et al. (2020). Emerging regulatory aspects of nanotechnology in the agri/feed/food sector in EU and non-EU countries. Regul. Toxicol. Pharmac. 73, 463–476. doi: 10.1016/j.yrtph.2015.06.016
Andersen, C. P., Kirby, J. K., and McLaughlin, M. J. (2013). Fate and risks of nanomaterials in aquatic and terrestrial environments. Acc. Chem. Res. 46, 854–862. doi: 10.1021/ar2003368
Behboudi, F., Tāhmasbi Sarvestani, Z., Kassaei, M. Z., Modares Sanavi, S. A., Sorooshzadeh, A., and Ahmadi, S. B. (2018). Evaluation of chitosan nanoparticles effects on yield and yield components of barley (Hordeum vulgare L.) under late season drought stress. J. Water. Environ. Nanotechnol. 3, 22–39. doi: 10.22090/JWEN.2018.01.003
Bhati, A. S., Sharma, S., Shukla, N., and Uttam, K. N. (2018). Steady state and time resolved laser-induced fluorescence of garlic plants treated with titanium dioxide nanoparticles. Spectrosc. Lett. 51, 45–54. doi: 10.1080/00387010.2017.1417871
Bin Hussein, M. Z., Yahaya, A. H., Zainal, Z., and Kian, L. H. (2005). Nanocomposite-based controlled release formulation of an herbicide, 2, 4-dichlorophenoxyacetate incapsulated in zinc–aluminium-layered double hydroxide. Sci. Technol. Adv. Mater. 6, 956–962. doi: 10.1016/j.stam.2005.09.004
Borgatta, J., Ma, C., Hudson-Smith, N., Elmer, W., Plaza Pérez, C. D., De La Torre-Roche, R., et al. (2018). Copper based nanomaterials suppress root fungal disease in watermelon (Citrus lanatus): role of particle morphology, composition and dissolution behavior. ACS. Sustain. Chem. Eng. 61, 4847–4856. doi: 10.1021/acssuschemeng.8b03379
Bos, P. M., Gottardo, S., Scott-Fordsmand, J. J., Van Tongeren, M. , Semenzin, E., Fernandes, T. F., et al. (2015). The marina risk assessment strategy: a flexible strategy for efficient information collection and risk assessment of nanomaterials. Int. J. Environ. Res. Public Health 12, 15007–15021. doi: 10.3390/ijerph121114961
Boykov, I. N., Shuford, E., and Zhang, R. (2019). Nanoparticle titanium dioxide affects the growth and microRNA expression of switchgrass (Panicum virgatum). Genomics 111, 450–456. doi: 10.6010/ijgnet.2018.03.002
Brambhanwade, K., Shende, S., Bonde, S., Gade, A., and Rai, M. (2016). Fungicidal activity of Cu nanoparticles against fusarium causing crop diseases. Environ. Chem. Lett. 14, 229–235. doi: 10.1007/s10311-015-0543-1
Buchmann, J. T., Elmer, W. H., Ma, C., Landy, K. M., White, J. C., and Haynes, C. L. (2015). Activity of Cu nanoparticles against fusarium causing crop diseases. Environ. Sci. Technol. 49, 11116-11124. doi: 10.1021/acs.est.5b04426
Cai, L., Cai, L., Jia, H., Liu, C., Wang, D., and Sun, X. (2020). Foliar exposure of FeO nanoparticles on Nicotiana benthamiana: evidence for nanoparticles

Frontiers in Nanotechnology | www.frontiersin.org
30 December 2020 | Article | 579594
Mittal et al.
Nanoparticles for Sustainable Agriculture
uptake, plant growth promoter and defense response elicitor against plant virus. J. Hazard. Mater. 393:122415. doi: 10.1016/j.jhazmat.2020.122415

Cai, L., Liu, M., Liu, Z., Yang, H., Sun, X., Chen, J., et al. (2018). MgO NPs can boost plant growth: evidence from increased seedling growth, morpho-physiological activities, and Mg uptake in tobacco (Nicotiana tabacum L.). Molecules 23:3375. doi:10.3390/molecules23123375

Cañas, J. E., Long, M., Nations, S., Vadan, R., Dai, L., Luo, M., et al. (2008). Effects of functionalized and nonfunctionalized single-walled carbon nanotubes on root elongation of select crop species. Environ. Toxicol. Chem. 27, 1922–1931. doi: 10.1897/08-117.1

Carlson, C., Hussain, S. M., Schrand, A. M., K., Braydich-Stolle, L., Hess, K. L., Mittal et al. Nanoparticles for Sustainable Agriculture

Cummins, C. M., Koivunen, M. E., Stephanian, A., Gee, S. J., Hammock, B. D., and Kennedy, I. M. (2006). Application of euriopium (III) chelate-dyed nanoparticles in a competitive atrazine fluoroimmunoassay on an ITO waveguide. Biosens. Bioelectron. 21, 1077–1085. doi: 10.1016/j.bios.2005.04.003

Cumplido-Nájera, C. F., González-Morales, S., Ortega-Ortíz, H., Cadenas-Piiego, G., Benavides-Mendoza, A., and Juárez-Maldonado, A. (2019). The application of copper nanoparticles and potassium silicate stimulate the tolerance to Clavibacter michiganensis in tomato plants. Sci. Hortic. 245, 82–89. doi: 10.1016/j.scienta.2018.10.007

da Costa, M. V. J., and Sharma, P. K. (2016). Effect of copper oxide nanoparticles growth, morphology, photosynthesis, and antioxidant response in Oryza sativa. Photosynthetic 54, 110–119. doi: 10.1007/s11099-015-0167-5

Dai, D., and Fan, M. (2013). Green modification of natural fibres with nanocellulose. RSC Adv. 3, 4659–4665. doi: 10.1039/c3ra22190b

Davis, R. A., Rippner, D. A., Hausner, S. H., Parikh, S. J., McLerone, A. J., and Sutcliffe, J. L. (2017). In vivo tracking of copper-64 radiolabeled nanoparticles in Lactuca sativa. Environ. Sci. Technol. 51, 12537–12546. doi: 10.1021/acs.est.7b03333

de Oliveira, L. J., Campos, E. V., Bakhsh, M., Abhilash, P. C., and Fraceto, L. F. (2014). Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotech. Adv. 32, 1550–1561. doi: 10.1016/j.biotechadv.2014.10.010

Delfani, M., Baradaran Firouzabadi, M., Farrokh, N., and Makarian, H. (2014). Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. Commun. Soil Sci. Plant Anal. 45, 530–540. doi:10.1080/00103624.2013.869111

Deng, Y., Petersen, E. J., Challis, K. E., Rabb, S. A., Holbrook, R. D., and Ranville, J. F. (2017). Multiple method analysis of TiO2 nanoparticle uptake in rice (Oryza sativa L.) plants. Environ. Sci. Technol. 51, 10615–10623. doi: 10.1021/acs.est.7b01364

Dhoke, S. K., Mahajan, P., Kamble, R., and Khanna, A. (2013). Effect of nanoparticles suspension on the growth of mung (Vigna radiata) seedlings by foliar spray method. Nanotechnol. Dev. 3, 104. doi:10.1081/ntd.2011.0311a

Dietz, K. J., and Herth, S. (2011). Plant nanotoxicology. Trends. Plant. Sci. 16, 582–589. doi:10.1016/j.plants.2011.08.003

Dimkpa, C. O., and Bindraban, P. S. (2016). Fortification of micronutrients for efficient agronomic production: a review. Agro. Sustain. Dev. 36:7. doi: 10.1007/s13593-015-0346-6

Dimkpa, C. O., and Bindraban, P. S. (2017). Nanofertilizers: new products for the industry? J. Agric. Food Chem. 66, 6462–6473. doi: 10.1021/acs.jafc.7b02150

Dimkpa, C. O., Bindraban, P. S., Fugise, J., Agyn-Birikorang, S., Singh, U., and Hellums, D. (2017a). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agro. Sustain. Dev. 37:5. doi:10.1007/s13593-016-0412-8

Dimkpa, C. O., White, J. C., Elmer, W. H., and Gardea-Torresdey, J. (2017b). Nanofertilizer and ionic Zn promote nutrient loading of sorghum grain under low NPK fertilization. J. Agric. Food Chem. 65, 8552–8559. doi: 10.1021/acs.jafc.7b02961

Djanaguiraman, M., Belliraj, N., Bossmann, S. H., and Prasad, P. V. (2018a). High-temperature stress alleviation by selenium nanoparticle treatment in grain sorghum. ACS Omega 3, 2479–2491. doi: 10.1021/acsomega.7b01934

Djanaguiraman, M., Nair, R., Giraldo, J. P., and Prasad, P. V. (2018b). Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS Omega 3, 14406–14416. doi:10.1021/acsomega.8b01894

Dogaroglu, Z. G., and Köleli, N. (2017). TiO2 and ZnO nanoparticles toxicity in barley (Hordeum vulgare L.). Clean Soil Air Water 45:1700096. doi: 10.1002/csa.201700996

Du, W., Sun, Y., Ji, R., Zhu, J., Wu, J., and Guo, H. (2011). TiO2 and ZnO nanoparticles negatively affect wheat growth and soil enzyme activities in agricultural soil. J. Environ. Monit. 13, 822–828. doi:10.1039/c0em00611d

Dwivedi, S., Saquib, Q., Al-Khedhairy, A. A., and Musarrat, J. (2016). Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. Commun. Soil Sci. Plant Anal. 45, 530–540. doi:10.1080/00103624.2013.869111

Eichler, T., Kurtz, A., Steitz, U., and Goldbach, H. E. (2008). Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles. Physiol. Plant. 134, 151–160. doi: 10.1111/j.1399-3054.2008.01135.x

Frontiers in Nanotechnology | www.frontiersin.org

31 December 2020 | Volume 2 | Article 579954
Elias, E. H., Flynn, R., Idowu, O. J., Reyes, J., Sanogo, S., and Schutte, B. J. (2019). Crop vulnerability to weather and climate risk: analysis of interacting systems and adaptation efficacy for sustainable crop production. *Sustainability* 11:6619. doi: 10.3390/su11236619

Elmer, W. H., and White, J. C. (2016). The use of metallic oxide nanoparticles to enhance growth of tomatoes and eggplants in disease infected soil or soilless medium. *Environ. Sci. Nano* 3, 1072–1079. doi: 10.1039/C6EN00146G

Elsherey, N. I., Helaly, M. N., El-Hoseiny, H. M., and Alam-Eldein, S. M. (2020). Zinc oxide and silicone nanoparticles to improve the resistance mechanism and annual productivity of salt-stressed mango trees. *Agronomy* 10:558. doi: 10.3390/agronomy10040558

Esser, B., Schorrn, J. M., and Swager, T. M. (2012). Selective detection of ethylene gas using carbon nanotube-based devices: utility in determination of fruit ripeness. *Angew. Chem. Int. Ed.* 51, 5752–5756. doi: 10.1002/anie.201201042

Faisal, M., Saqib, Q., Alatar, A. A., Al-Khedhairy, A. A., Hegazy, A. K., and Musarrat, J. (2013). Phytotoxic hazards of NiO-nanoparticles in tomato: a study on mechanism of cell death. *J. Hazard. Mat.* 250, 318–332. doi: 10.1016/j.jhazmat.2013.01.063

Falco, W. F., Scherer, M. D., Oliveira, S. L., Wender, H., Colbeck, I., Lawson, T., et al. (2020). Phytotoxicity of silver nanoparticles on *Vicia fava* evaluation of particle size effects on photosynthetic performance and leaf gas exchange. *Sci. Total Environ.* 701:134816. doi: 10.1016/j.scitotenv.2019.134816

Fan, P., Gu, Z., Xu, D., Xu, X., and Xu, G. (2010). Action analysis of drops of emanation-benzene microemulsion on rice leaf. *Chine. J. Rice Sci.* 24, 503–508. doi: 10.3969/j.issn.1001-7216.2010.05.010

Fang, Y., Umasankar, Y., and Ramasamy, R. P. (2014). Electrochemical detection of p-ethylguaiacol, a fungi infected fruit volatile using metal oxide nanoparticles. * Analyst* 139, 3804–3810. doi: 10.1039/C4AN00384E

Faraji, J., and Sepehri, A. (2020). Exogenous nitric oxide improves the protective effects of tiO nanoparticles on growth, antioxidant system, and photosynthetic efficiency of wheat seedlings under drought stress. *J. Soil. Sci. Plant Nutr.* 20, 703–714. doi: 10.1076/jsfp.2019.01-0158-0

Feng, Y., Cui, X., He, S., Dong, G., Chen, M., Wang, J., et al. (2013). The role of merlot nanoparticles in influencing arbuculus mycorrhizal fungi effects on plant growth. *Environ. Sci. Technol.* 47, 9496–9504. doi: 10.1021/es402169m

Foyer, C. H., and Noctor, G. (2005). Redox homeostasis and antioxidant signaling: a metabolic interface between stress perception and physiological responses. *Plant. Cell.* 17, 1866–1875. doi: 10.1105/tpc.105.033589

Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., and Bartolucci, C. (2016). Nanotechnology in agriculture: which innovation potential does it have? *Front. Environ. Sci.* 4. doi: 10.3389/fenvs.2016.00020

Frazee, T. P., Burklew, C. E., and Zhang, B. (2014). Titanium dioxide nanoparticles affect the growth and microRNA expression of tobacco (*Nicotiana tabacum*). *Front. Plant Sci.* 5:1341. doi: 10.3389/fpls.2014.01341

Gao, G., Tester, M. A., and Julkowska, M. M. (2020). The use of high-throughput phytotoxicity of CeO2 nanoparticles on lettuce cultured in the potting soil medium. *Lab. Chip* 20:15. doi: 10.1039/C9LC00874G

Gohari, G., Mohammadii, A., Akbari, A., Panahirad, S., Dadpour, M. R., Fotopoulos, V., et al. (2020). Titanium dioxide nanoparticles (TiO2 NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of Dracaena medinavica. *Sci. Rep.* 10:9121. doi: 10.1038/s41598-020-7794-1

Govea-Alcaide, E., Masunaga, S. H., De Souza, A. Fajardo-Rosabal, L., Effenberger, F. B., Rossi, L. M., et al. (2016). Tracking iron oxide nanoparticles in plant organs using magnetic measurements. *J. Nan. Res.* 18:305. doi: 10.1007/s11551-016-3610-z

Gowayed, M. H., Al-Zahrani, H. S., and Metwali, E. M. (2017). Improving the salinity tolerance in potato (*Solanaus tuberosum*) by exogenous application of silicic acid dioxide nanoparticles. *Int. J. Agric. Biol.* 19, 183–194. doi: 10.1795/ijab.15.0262

Graham, J. H., Johnson, E. G., Myers, M. E., Young, M., Rajasekaran, P., Das, S., et al. (2016). Potential of nano-formulated zinc oxide for control of citrus canker on grapefruit trees. *Plant. Dis.* 100, 2442–2447. doi: 10.1094/PDIS-05-16-0598-RE

Guy, X., Zhang, Z., Liu, S., Ma, Y., Zhang, P., He, X., et al. (2015). Fate and phytotoxicity of CeO2 nanoparticles on lettuce cultured in the potting soil environment. *PLos ONE* 10:e0134261. doi: 10.1371/journal.pone.0134261

Guo, Y. R., Liu, S. Y., Gui, W. J., and Zhu, G. N. (2009). Gold immunocolorimetric assay for simultaneous detection of carbofuran and triazophos in water samples. *Anal. Biochem.* 389, 32–39. doi: 10.1016/j.ab.2009.03.020

Guo, Z., Park, S., Yoon, J., and Shin, I. (2014). Recent progress in the development of near-infrared fluorescent probes for bioimaging applications. *Chem. Rev.* 114, 43–29. doi: 10.1021/cr300271K

Haghighi, M., Abolhassemi, R., and da Silva, J. A. T. (2014). Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. *Sci. Horticult.* 178, 231–240. doi: 10.1016/j.scienta.2014.09.006

Haghighi, M., and Pessarakli, M. (2013). Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (*Solanum lycopersicum*) at early growth stage. *Sci. Horticult.* 161, 111–117. doi: 10.1016/j.scienta.2013.06.034

Hao, Y., Yu, F., Lv, R., Ma, C., Zhang, Z., Rui, Y., et al. (2016). Carbon nanotubes filled with different ferromagnetic alloys affect the growth and development of rice seedlings by changing the C: N ratio and plant hormones concentrations. *PLos ONE* 11:e0157264. doi: 10.1371/journal.pone.0157264

Hatami, M. (2017). Toxicity assessment of multi-walled carbon nanotubes on *Cucurbita pepo* L. under well-watered and water-stressed conditions. *Ecotoxicol. Environ. Safety* 142, 274–283. doi: 10.1016/j.ecoenv.2017.04.018

Hatfield, J. L., Gitelson, A. A., Schepers, J. S., and Walthall, C. L. (2008). Application of spectral remote sensing for agronomic decisions. *Agron. J.* 100, 117–131. doi: 10.2134/agronj2006.0370c

Hauser, F., and Horie, T. (2010). A conserved primary salt tolerance mechanism across plant species: characterization and evaluation of copper based nanoparticles as agrochemicals against *Phytophthora infestans*. *RSC Adv.* 3, 21743–21752. doi: 10.1039/C3RA24118H

Gilroy, S., Suzuki, N., Miller, G., Choi, W. G., Toyota, M., Devireddy, A. R., et al. (2013). A tidal wave of signals: calcium and ROS at the forefront of rapid systemic signaling. *Trends. Plant. Sci.* 19, 623–630. doi: 10.1016/j.ptspan.2014.06.013

Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., et al. (2014). Plant nanobiomics approach to augment photosynthesis and biochemical sensing. *Nat. Mater.* 13, 400–408. doi: 10.1038/nmat3890
(2018). Effects of chitosan–PVA and Cu nanoparticles on the growth and antioxidant capacity of tomato under saline stress. *Molecules* 23:178. doi: 10.3390/molecules23010178
Ho, V. A., Le, P. T., Nguyen, T. P., Nguyen, C. K., Nguyen, V. T., and Tran, N. Q. (2015). Silver core-shell nanoclusters exhibiting strong growth inhibition of plant-pathogenic fungi. *J. Nanomater*. 2015:241614. doi: 10.1155/2015/241614
Hojat, S. S., and Kamaly, M. (2017). The effect of silver nanoparticle on Fenugreek seed germination under salinity levels. *Russian. Agricul. Sci*. 43, 61–65. doi: 10.3103/S0168674117010189
Hong, G., Diao, S., Antaris, A. L., and Dai, H. (2015). Carbon nanoparticles for biological imaging and nanomedicinal therapy. *Chem. Rev*. 115, 10816–10906. doi: 10.1021/acs.chemrev.5b00008
Hotze, E. M., Phenrat, T., and Lowry, G. V. (2010). Nanoparticle aggregation: challenges to understanding transport and reactivity in the environment. *J. Environ. Qual*. 39, 1909–1924. doi: 10.2134/jeq2009.0462
Hu, P., An, J., Faulkner, M. M., Wu, H., Li, Z., Tian, X., et al. (2020). nanoparticle charge and size control foliar delivery efficiency to plant cells and organelles. *ACS. Nano* 14, 7970–7986. doi: 10.1021/acsnano.9b09178
Hua, X., Qian, G., Yang, J., Hu, B., Fan, J., Qin, N., et al. (2010). Development of an immunochromatographic assay for the rapid detection of chlorpyrifos-methyl in water samples. *Biosens. Bioelectron*. 26, 189–194. doi: 10.1016/j.bios.2010.06.005
Huang, U., Ullah, F., Zhou, D. X., Yi, M., and Zhao, Y. (2019). Mechanisms of ROS regulation of plant development and stress responses. *Front. Plant. Sci*. 10:800.
Huang, S., Wang, L., Liu, L., Li, Z., Tian, X., et al. (2020). nanoparticle and nanoparticles affect early growth, flowering time and phytohormones in tomato. *Chemosphere* 256:127042. doi: 10.1016/j.chemosphere.2020.127042
Ji, M., Navarrete-Lugo, M., Wickramasinghe, S., Milbrandt, N. B., McWhorter, A., and Samia, A. C. (2019). Exploring the chelation-based plant strategy for iron oxide nanoparticle uptake in garden cress (*Lepidium sativum*) using magnetic particle spectrometry. *Nanoscale* 11, 18582–18594. doi: 10.1039/C9NR05477D
Juárez-Maldonado, A., Ortega-Ortíz, H., Morales-Díaz, A. R., González-Morales, S., Morelos-Moreno, Á., Sandoval-Valencia, A., et al. (2019). Nanoparticles and nanomaterials as plant bio-stimulants. *Int. J. Mol. Sci*. 20:162. doi: 10.3390/ijms20010162
Kang, Y., Khan, S., and Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security—a review. *Progress. Nat. Sci.* 19, 1665–1674. doi: 10.1016/j.pnsc.2009.08.001
Karamian, R., Ghasemlou, P., and Amiri, H. (2020). Physiological evaluation of drought stress tolerance and recovery in *Verbascum sinuatum* plants treated with methyl jasmonate, salicylic acid and titanium dioxide nanoparticles. *Plant Biosys. Int. J. Deal. Aspect. Plant. Biol*. 154, 277–287. doi: 10.1101/2019.159153
Kaur, T., Singh, G. P., Kaur, G., Kaur, S., and Gill, P. K. (2016). Synthesis of biogenic silicon/silica (Si/SiO₂) nanocomposites from rice husks and wheat bran through various microorganisms. *Mater. Res. Exp*. 3:085026. doi: 10.1088-2053-1193/8/085026
Keller, A. A., Huang, Y., and Nelson, J. (2018). Detection of nanoparticles in edible plant tissues exposed to nano-copper using single-particle ICP-MS. *J. Nano. Res*. 20:101. doi: 10.1007/s11604-018-1494-2
Khan, M. N., Al-Solami, M. A., Basahi, R. A., Siddiqui, M. H., Al-Huqail, A. A., Abbas, Z. K., et al. (2020). Nitric oxide is involved in nano-titanium dioxide-induced activation of antioxidant defense system and accumulation of osmolytes under water-deficit stress in *Vicia faba* L. *Ecotoxicol. Environ. Saf*. 190:11152. doi: 10.1016/j.ecoenv.2019.111522
Khodakovskaya, M. V., De Silva, K., Biris, A. S., Dervishi, E., and Villagarcía, H. (2012). Carbon nanotubes induce growth enhancement of tobacco cells. *ACS Nano* 6, 2128–2135. doi: 10.1021/nn204643g
Kim, T. H., Böhmér, M., Hu, H., Nishimura, N., and Schroeder, J. I. (2010). Guard cell signal transduction network: advances in understanding abscisic acid, CO₂, and Ca²⁺ signaling. *Ann. Review. Plant. Biol*. 61, 561–591. doi: 10.1146/annurev-plant.042809-112226
Kraegeloh, A., Suarez-Merino, B., Sluiters, T., and Micheletti, C. (2018). Implementation of safe-by-design for nanomaterial development and safe innovation: why we need a comprehensive approach. *Nanomaterials* 8:2329. doi: 10.3390/nano810239
Kranthi, K. R., Davis, M., Mayee, C. D., Russell, D. A., Shukla, R. M., Satija, U., et al. (2009). Development of a colloidal-gold based lateral-flow immunoassay kit for ‘quality-control’ assessment of pyrethroid and endosulfan formulations in a novel single strip format. *Crop Prot*. 28, 428–434. doi: 10.1016/j.cropro.2009.01.003
Kruss, S., Landry, M. P., Vander Ende, E., Lima, B. M., Reuel, N. F., Zhang, J., et al. (2014). Neurotransmitter detection using corona phase molecular recognition on fluorescent single-walled carbon nanotube sensors. *J. Amer. Chem. Soc*. 136, 713–724. doi: 10.1021/ja410433b
Kumar, R. S., Shiny, P. J., Anjali, C. H., Jerobin, J., Goshen, K. M., and Magdassi, S. (2013). Distinctive effects of nano-sized permethrin in the environment. *Environ. Sci. Pollut. Res. Int*. 20, 2593–2602. doi: 10.1007/s11356-012-1161-0
Kumbhakar, P., Ray, S. S., and Stepanov, A. L. (2014). Optical properties of nanoparticles and nanocomposites. *J. Nanomater*. 2014:81365. doi: 10.1155/2014/81365
Lahiani, M. H., Dervishi, E., Chen, J., Nima, Z., Gaume, A., Biris, A. S., et al. (2014). Fate of pristine TiO₂ nanoparticles in lettuce crop after foliar exposure. *J. Hazard Mat*. 273, 16–26. doi: 10.1016/j.jhazmat.2014.03.014
Larue, C., Castillon-Michel, H., Sobanska, S., Trcera, N., Soriel, S., Cécillon, L., et al. (2014). Fate of pristine TiO₂ nanoparticles and aged paint-containing TiO₂ nanoparticles in lettuce crop after foliar exposure. *J. Hazard Mat*. 273, 16–26. doi: 10.1016/j.jhazmat.2014.03.014
Larue, C., LaRiviere, J., Herlin-Boimare, X., Khodja, H., Fayard, B., and Flank, A. M. (2012a). Accumulation, translocation and impact of TiO₂ nanoparticles in wheat (*Triticum aestivum* spp.): influence of diameter and crystal phase. *Sci. Total Environ.* 431, 197–208. doi: 10.1016/j.scitotenv.2012.04.073
Larue, C., Pinault, M., Czarny, B., Georgin, D., Jaillard, D., Bendiab, N., et al. (2012b). Quantitative evaluation of multi-walled carbon nanoparticle uptake in wheat and rapeseed. J. Hazard. Mater. 227, 155–163. doi: 10.1016/j.jhazmat.2012.05.033

Lee, K., Park, J., Lee, M. S., Kim, J., Hyun, B. G., Kang, D. J., et al. (2014). In-situ synthesis of carbon nanotube–graphite electronic devices and their integrations onto surfaces of live plants and insects. Nano Lett. 14, 2647–2654. doi: 10.1021/nl500513n

Leso, V., Fontana, L., and Iavicoli, I. (2019). Biomedical nanotechnology: occupational views. Nano Today 24, 10–14. doi: 10.1016/j.nantod.2018.11.002

Li, R., He, J., Xie, H., Wang, W., Bose, S. K., Sun, Y., et al. (2019). Influence of silver nitrate nanoparticles on soybean (Glycine max) plants. Environ. Sci. Technol. 44, 7215–7220. doi: 10.1021/acs.est.9b03918

Lopez-Moreno, M. L., de la Rosa, G., Hernandez-Viecas, J. A., Castillo-Michel, H., Botez, C. E., Peralta-Videa, J. R., et al. (2010). Evidence of the differential biotransformation and genotoxicity of ZnO and CeO2 nanoparticles on soybean (Glycine max) plants. Environ. Sci. Technol. 44, 7215–7220. doi: 10.1021/acs.est.9b03918

Liu, X. M., Feng, Z. B., Zhang, F. D., Zhang, S. Q., and He, X. S. (2006). Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. J. Environ. Sci. Total. Environ. 32, 1128–1132. doi: 10.1016/s0048-9697(05)62515-2

Liu, J., Hu, W., Santana, I., Fahlgren, M., and Giraldo, J. P. (2018). Standoff optical glucose sensing in photosynthetic organisms by a quantum dot fluorescent probe. ACS Appl. Mater. Interf. 10, 28279–28289. doi: 10.1021/acsami.8b07179

Liu, R., He, J., Xie, H., Wang, W., Bose, S. K., Sun, Y., et al. (2019). Effects of chitosan nanoparticles on seed germination and seedling growth of wheat (Triticum aestivum L.). Int. J. Biol. Macromol. 126, 91–100. doi: 10.1016/j.ijbiomac.2018.12.118

Liu, W. Q., Qing, T., Li, C. C., Li, F., Ge, F., Fei, J. J., et al. (2020). Integration of subcellular partitioning and chemical forms to understand silver nanoparticles toxicity to lettuce (Lactuca sativa L.) under different exposure pathways. Chemosphere 258:127349. doi: 10.1016/j.chemosphere.2020.127349

Li, Y., Jin, Q., Yang, D., and Cui, J. (2018). Molybdenum sulfide induce growth enhancement effect of rice (Oryza sativa L.) through regulating the synthesis of chlorophyll and the expression of aquaporin gene. J. Agric. Food. Chem. 66, 4013–4021. doi: 10.1021/acs.jafc.7b03940

Lin, S., Reppert, J., Hu, Q., Hudson, J. S., Reid, M. L., Ratnikova, T. A., et al. (2009). Uptake, translocation, and transmission of carbon nanomaterials in rice plants. Small 5, 1128–1132. doi: 10.1002/smll.200801556

Liska, K.P., and Pradeep, T. (2009). Enhanced visual detection of pesticides using gold nanoparticles. J. Environ. Sci. Health Part B 44, 697–705. doi: 10.1080/03601230903163814

Liu, F., Wen, L. X., Li, Z. Z., Yu, W., Sun, H. Y., and Chen, J. F. (2006). Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. Mater. Res. Bull. 41, 2268–2275. doi: 10.1016/j.materresbull.2006.04.014

Liu, M., Feng, S., Ma, Y., Xie, C., He, X., Ding, Y., et al. (2019). Influence of sunlight on the phototoxicity, transformation, and translocation of CeO2 nanoparticles in cucumber plants. ACS Appl. Mater. Interf. 11, 16905–16913. doi: 10.1021/acsami.9b01627

Liu, R., and Lal, R. (2015). Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). Sci. Rep. 5:6866. doi: 10.1038/srep05686

Liu, R., Zhang, H., and Lal, R. (2016). Effects of stabilized nanoparticles of copper, zinc, manganese, and iron oxides in low concentrations on lettuce (Lactuca sativa) seed germination: nanotoxicants or nanonutrients? Water. Air. Soil. Poll. 227:42. doi: 10.1007/s11270-015-2738-2

Liu, X., Zhang, F., Zhang, S., He, X., Wang, B., Fei, Z., et al. (2005). Responses of peanut to nano-calcium carbonate. Plant Nutri. Ferti. Sci. 11, 385–389.

Liu, X. M., Feng, Z. B., Zhang, F. D., Zhang, S. Q., and He, X. S. (2006). Preparation and testing of cementing and coating nano-subnanocomposites of slow/controlled-release fertilizer. Agricult. Sci. China 5, 700–706. doi: 10.1007/s11671-2927/060113-2

Liu, Y., and Shi, J. (2019). Antioxidative nanomaterials and biomedical applications. Nano Today 27, 146–177. doi: 10.1016/j.nantod.2019.05.008

Lombi, E., Donner, E., Dusinska, M., and Wickson, F. (2019). A one health approach to managing the applications and implications of nanomaterials in agriculture. Nat. Nanotechnol. 14, 523–531. doi: 10.1038/s41565-019-0460-8

López, M. M., Llop, P., Olmos, A., Marco-Noales, E., Cambra, M., and Bertolini, E. (2009). Are molecular tools solving the challenges posed by detection of plant pathogenic bacteria and viruses? Curr. Issues Mol. Biol. 11, 13–46.
Ocsoy, I., Paret, M. L., Ocsoy, M. A., Kunwar, S., Chen, T., You, M., et al. (2013). Cytokinin cross-talk during biotic and abiotic stress responses. Front. Plant Sci. 4, 451. doi: 10.3389/fpls.2013.00451

Ocsoy, I., Paret, M. L., Ocsoy, M. A., Kunwar, S., Chen, T., You, M., et al. (2013). Nanotechnology in plant disease management: DNA directed silver nanoparticles on grapevine oxide as an antibacterial against Xanthomonas perforans. Acas Nano. 7, 8972–8980. doi: 10.1016/j.nanosco.2013.04.794

Oliveira, H. C., Stolf-Moreira, R., Martinez, C. B., Grillo, R., de Jesus, M. B., and Fraceto, L. F. (2015). Nanoencapsulation enhances the post-emergence herbicidal activity of atrazine against mustard plants. PLoS ONE 10:e0132971. doi: 10.1371/journal.pone.0132971

Ohman, S. H. (2014). Bio-nanocomposite materials for food packaging applications: types of biopolymer and nano-sized filler. Agric. Sci. Proc. 2, 296–303. doi: 10.1016/j.asaprocpro.2014.11.042

Ouda, S. M. (2014). Antifungal activity of silver and copper nanoparticles on two plant pathogens, Alternaria alternata and Botrytis cinerea. Res. J. Microbiol. 9, 34–42. doi: 10.3923/jrm.2014.34.42

Padilla, F. M., Gallardo, M., Peña-Fleitas, M. T., De Souza, R., and Thompson, R. B. (2018). Proximal optical sensors for nitrogen management of vegetable crops: a review. Sensors 18:2083. doi: 10.3390/s18072083

Palchoudhury, S., Jungjohann, K. L., Weerasena, L., Arabshahi, A., Gharie, U., Albattah, A., et al. (2018). Enhanced legume root growth with presoaking in α-Fe2O3 nanoparticle fertilizer. RSC Adv. 8, 24075–24083. doi: 10.1039/C8RA04680H

Palmqvist, M. N., Seisenbaeva, A. G., Svedlindh, P., and Kessler, V. G. (2017). Maghemite nanoparticles acts as nanozymes, improving growth and abiotic stress tolerance in Brassica napus. Nanosc. Res. Lett. 12:631. doi: 10.1186/s11671-017-2404-2

Patel, M. L., Vallad, G. E., Averett, D. R., Jones, J. B., and Olson, S. M. (2013). Comparative phytotoxicity of ZnO nanoparticles, ZnO micro nanoparticles, and Zn2+ on rapeseed (Brassica napus L): investigating a wide range of concentrations. Toxicol. Environ. Chem. 96, 861–868. doi: 10.1080/02777218.2014.994517

Mozafari, A., Havas, F., and Ghaderi, N. (2018). Application of iron nanoparticles and salicylic acid in in vitro culture of strawberries (Fragaria x ananassa Duch.) to cope with drought stress. Plant. Cell. Tiss. Organ. Cult. 132, 511–523. doi: 10.1007/s11240-017-1347-8

Nel, A., Xia, T., Mädler, L., and Li, N. (2006). Toxic potential of materials at the nanoscale. Science 313, 622–627. doi: 10.1126/science.1114397

Narayanan, K. B., and Park, H. H. (2014). Antifungal activity of silver nanoparticles synthesized using turnip leaf extract (Brassica rapa L.) against wood rotting pathogens. Eur. J. Plant. Pathol. 140, 185–192. doi: 10.1007/s10658-014-0394-9

Nath, J., Dror, I., Landa, P., Vanek, T., Kaplan-Ashiri, I., and Berkowitz, B. (2018). Synthesis and characterization of isotopically-labeled silver, copper and zinc oxide nanoparticles for tracing studies in plants. Environ. Pollut. 242, 1827–1837. doi: 10.1016/j.envpol.2017.08.074

Navarro, D. A., Bisson, M. A., and Ága, D. S. (2012). Investigating uptake of water-dispersible CdSe/ZnS quantum dot nanoparticles by Arabidopsis thaliana plants. J. Hazard. Mater. 211, 427–435. doi: 10.1016/j.jhazmat.2011.12.012

Nel, A., Xia, T., Madler, L., and Li, N. (2006). Toxic potential of materials at the nanoscale. Science 313, 622–627. doi: 10.1126/science.1114397

Niecola, C. V., Carvalho, C. P., Barcelos, R., and Rodrigues, E. (2017). Rapid responses of plants to temperature changes. Temperature. 4, 371–405. doi: 10.1007/s42388-017-1377812

Nuruzzaman, M. D., Rahman, M. M., Liu, Y., and Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J. Agric. Food Chem. 64, 1447–1483. doi: 10.1021/acs.jafc.5b05214

O’Brien, J. A., and Benková, E. (2013). Cytokinin cross-talking during biotic and abiotic stress responses. Front. Plant Sci. 4:451. doi: 10.3389/fpls.2013.00451

Qi-jiang, H., Wei-jin, Z. H., Feng-ming, L. I., Dong-mei, S. H., Chun-hua, Z. H., and Xiao-li, B. U. (2006). Solubilization of chlorpyrifos in the mixed system of surfactants and the bioactivity evaluation. J. Chin. J. Pesticide Sci. 8, 71–76.
Rajput, V., Minkina, T., Fedorenko, A., Sushkova, S., Mandzhieva, S., Lysenko, R., Rajesh, S., Raja, D. P., Rathi, J. M., and Sahayaraj, K. (2018). Iron oxide nanoparticles as a potential iron fertilizer for peanut (Arachis hypogaea). Front. Plant. Sci. 7:815. doi: 10.3389/fpls.2016.00815

Saharan, V., Kumaraswamy, R. V., Choudhary, R. C., Kurnani, S., Pal, A., Raliya, R., et al. (2016). Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. J. Agric. Food Chem. 64, 6148–6155. doi: 10.1021/jf5112239

Saharan, V., Mehratra, A., Khatik, R., Rawal, P., Sharma, S. S., and Pal, A. (2013). Synthesis of chitosan based nanoparticles and their in vitro evaluation against phytopathogenic fungi. Int. J. Biol. Macromol. 62, 677–683. doi: 10.1016/j.ijbiomac.2013.10.012

Santiago, M., Pagay, V., and Strook, A. D. (2013). Impact of electroviscousity on the hydraulic conductance of the bordered pit membrane: a theoretical investigation. Plant Physiol. 163, 999–1011. doi: 10.1104/pp.113.219774

Sarla, N., Taheriâ, A., and Salehi, F. (2014). Synthesis of nanopesticides by encapsulating pesticide nanoparticles using functionalized carbon nanotubes and application of new nanocomposite for plant disease treatment. J. Agric. Food Chem. 62, 4833–4838. doi: 10.1021/jf404720d

Sasson, Y., Levy-Ruso, G., Toledano, O., and Issaya, I. (2007). "Nanosuspensions: emerging novel agrochemical formulations," in Insecticides Design Using Advanced Technologies (Berlin; Heidelberg: Springer), 1–39. doi: 10.1007/978-3-540-46097-0_1

Sattelmacher, B. (2001). The apoplast and its significance for plant mineral nutrition. New Phytol. 149, 167–192. doi: 10.1046/j.1469-8137.2001.00334.x

Saxena, R., Tomar, R. S., and Kumar, M. (2016). Exploring nanobiotechnology to mitigate abiotic stress in crop plants. J. Pharma. Sci. 98.974.

Schwab, F., Zhai, G., Kern, M., Turner, A., Schnoor, J. L., and Wiesner, M. R. (2016). Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants–critical review. Nanotoxicology 10, 257–278. doi: 10.1016/j.ijbiomac.2013.10.012

Sedghi, M., Hadi, M., and Tolue, S. G. (2013). Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. Annal. West Univ. Timisoara ser Bot. 16, 73–78.

Servin, A. D., and White, J. C. (2016). Nanotechnology in agriculture: next steps for understanding engineered nanoparticle exposure and risk. NanoImpact 1, 9–12. doi: 10.1016/j.nanoimpact.2015.12.002

Shah, M. A., and Khan, A. A. (2014). Use of diatomaceous earth for the management of stored-product pests. Int. J. Pest Manag. 60, 100–113. doi: 10.1080/09670874.2014.918674

Shahabi-Ghahafarrokhi, I., Khodaiyan, F., Mousavi, M., and Yousefi, H. (2015). Preparation and characterization of nanocel lulose from beer industrial residues using acid hydrolysis/ultrasound. Fibers Polym. 16, 529–536. doi: 10.1016/j.surfact.2015.03.005

Shakoor, H., Hossein-Ikhan, B., and Emiztaei, G. (2014). The nano- bioceramic in antibacterial nitrates reductase. J. Bioproc. Biotechn. 4:4. doi: 10.4172/2155-9821.1000162

Shallan, M. A., Hassan, H. M., Namish, A. A., and Ibrahim, A. A., (2016). Biochemical and physiological effects of TiO2 and SiO2 nanoparticles on cotton plant under drought stress. Res. J. Pharma. Bio. Chem. Sci. 7, 1540–1551.

Sharifi, M., Farzab, I., Taleai, A. J., Shekha, M. S., Alle-Ebrahim, M., and Salahi, A. (2020). Antioxidant properties of gold nanozyme: a review. J. Mol. Liq. 297:112004. doi: 10.1016/j.molliq.2019.112004

Shahab, M. A., dust, D. B., and Pessarakli, M. (2012). Reactive oxygen species, oxidative damage, and antioxidative defense mechanisms in plants under stressful conditions. J. Exp. Bot. 52, 2033–2032. doi: 10.1093/jxbert/52.363.2023

Cicero, M., Majumdar, S., Suarte-Gardea, M., Peralt-Videa, J. R., and Gardea-Torresdey, J. L. (2011). Interaction of nanoparticles with edible plants and their possible implications in the food chain. J. Agric. Food Chem. 59, 3485–3498. doi: 10.1021/jf2004517

Riederer, M., and Schreiber, L. (2001). Protecting against water loss: analysis of the barrier properties of plant cuticles. J. Exp. Bot. 52, 2033–2032. doi: 10.1093/jexbot/52.363.2023

Roberts, A., and Opara, K. J. (2003). Plasmodiometry and the control of symbiotic transport. Plant Cell Environ. 26, 103–124. doi: 10.1046/j.1365-3040.2003.09950.x

Rossi, L., Zhang, W., Lombardini, L., and Ma, X. (2016). The impact of cerium oxide nanoparticles on the salt stress responses of Brassica napus L. Environ. Pol., 219, 28–36. doi: 10.1016/j.envpol.2016.09.060

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to the crop plants Solanum lycopersicum and brassica oleracea var. botrytis. J. Biotechnol. 262, 11–27. doi: 10.1016/j.jbiotec.2017.09.016

Singh, S., Singh, M., Agrawal, V. V., and Kumar, A. (2010). An attempt to develop surface plasmon resonance based immunosensor for Karnal bunt (Tilletia indica) diagnosis based on the experience of nano-gold based lateral flow immuno-dipstick test. Thin Solid Films 519, 1156–1159. doi: 10.1016/j.tsf.2010.08.061

Solanki, P., Bhargava, A., Chhipa, H., Jain, N., and Panwar, J. (2015). “Nano-fertilizers and their smart delivery system,” in Nanotechnologies in Food and Agriculture, ed M. Rai (Cham: Springer), 81–101. doi: 10.1007/978-3-319-14024-7_4

Soleymanzadeh, R., Iranbakhsh, A., Habibi, G., and Ardebili, Z. O. (2020). Selenium nanoparticle protected strawberry against salt stress through modifications in salicylic acid, ion homeostasis, antioxidant machinery, and photosynthesis performance. Acta. Biol. Cracoviensia. Botan. 62, 33–42.

Sotoodehnia-Korani, S., Iranbakhsh, A., Ebadi, M., Majd, A., and Ardebili, Z. O. (2020). Selenium nanoparticles induced variations in growth, morphology, anatomy, biochemistry, gene expression, and epigenetic DNA methylation in Capsicum annum: an in vitro study. Environ. Poll. 265:114727. doi: 10.1016/environpol.2020.114727

Souza, L. R. R., Bernardes, L. E., Barbetta, M. F. S., and da Veiga, M. A. M. S. (2019). Delivery, uptake, fate, and transport of engineered nanoparticles in plants. Environ. Sci. Nano 6, 2508–2519. doi: 10.1039/C9EN00626E

Stadler, T., Buteler, M., Valdez, S. R., and Gitto, J. G. (2018). Particulate nanoinsecticides: a new concept in insect pest management. Insectic. Agricul. Toxicol. 85:72448. doi: 10.5772/intechopen.72448

Stadler, T., Buteler, M., and Weaver, D. K. (2010). Novel use of nanostructured alumina as an insecticide. Pest Manage. Sci. 66, 577–579. doi: 10.1002/ps.1915

Stampoulis, D., Sinha, S. K., and White, J. C. (2009). Assay-dependent phytotoxicity of nanoparticles to plants. Environ. Sci. Technol. 43, 9473–9479. doi: 10.1021/es901695c

Stefan, L., and Monchaud, D. (2019). Applications of guanine quartets in nanotechnology and chemical biology. Nat. Rev. Chem. 3, 650–668. doi: 10.1038/s41570-019-0132-0

Stone, V., Führ, M., Feindt, P. H., and Führ, M., Feindt, P. H., Bouwmeester, H., Linkov, I., Sabella, S., et al. (2010). The essential elements of a risk governance framework for current and future nanotechnologies. Risk. Anal. 30, 1321–1331. doi: 10.1111/j.1539-6924.2010.01573.x

Su, Y., Ashworth, V. E., Geitner, N. K., Wiesner, M. R., Ginnan, N., Rolshausen, P., et al. (2020). Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (Triticum aestivum) seedlings. Plant Physiol. Biochem. 110, 70–81. doi: 10.1016/j.plaphy.2016.06.026

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., and Rehman, H., et al. (2020). Nanotechnology in agriculture: current status, challenges and future opportunities. Sci. Total. Environ. 721:137778. doi: 10.1016/j.scitotenv.2020.137778

Van Ha, C., Van Nguyen, D., Nguyen, H. M., Li, N. T., Nguyen, K. H., Le, H. M., et al. (2020). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. Biores. [Preprint]. doi: 10.1016/j.biores.2020.02.24.96312

Vankova, R., Landa, P., Podlipna, R., Dobrek, P. L., Prerostova, S., Langhansova, L., et al. (2017). ZnO nanoparticle effects on hormonal pools in Arabidopsis thaliana. Sci. Total. Environ. 593, 535–542. doi: 10.1016/j.scitotenv.2017.03.160

Vermala, R., Ravindran, P., and Kumar, P. P. (2016). Plant hormone-mediated regulation of stress responses. BMC Plant. Biol. 16:86. doi: 10.1186/s12870-016-0771-y

Vinayaka, A. C., Basheer, S., and Thakur, M. S. (2009). Bioconjugation of CdTe quantum dot for the detection of 2,4-dichlorophenoxyacetic acid by competitive fluoroimmunoassay based biosensor. Biosens. Bioelectro. 24, 1615–1620. doi: 10.1016/j.bios.2008.08.042

Vinayaka, A. C., and Thakur, M. S. (2010). Focus on quantum dots as potential fluorescent probes for monitoring food toxicants and foodborne pathogens. Anal. Bioanal. Chem. 397, 1445–1455. doi: 10.1007/s00216-010-3683-y

Wakeel, A., Xu, M., and Gan, Y., et al. (2020). Chromium-induced reactive oxygen species accumulation by altering the enzymatic antioxidant system and associated cytoxic, genotoxic, ultrastructural, and photosynthetic changes in plants. Int. J. Mol. Sci. 21:728. doi: 10.3390/ijms21030728

Wang, H., Hou, X., Pei, Z., Xiao, J. Q., Shan, X., and Xing, B. (2011). Physiological effects of magnetite (Fe3O4) nanoparticles on perennial ryegrass (Lolium perenne L.) and pumpkin (Cucurbita mixta) plants. Nanotoxicology 5, 30–42. doi: 10.3109/17435390.2010.489206

Wang, J., Koo, Y., Alexander, A., Yang, Y., Westerhof, S., Zhang, Q., et al. (2013). Phytostimulation of poplars and Arabidopsis exposed to silver nanoparticles and Ag+ at sublethal concentrations. Environ. Sci. Technol. 47, 5442–5449. doi: 10.1021/es404334

Wang, P., Lombi, E., Zhao, F. L., and Kopittke, P. M. (2016). Nanotechnology: a new opportunity in plant sciences. Trends Plant Sci. 21, 699–712. doi: 10.1016/j.tplants.2016.04.005

Wang, Q., Ma, X., Zhang, W., Pei, H., and Chen, Y. (2012). Effect of cerium oxide nanoparticles on tomato (Lycopersicon esculentum) plants under drought stress conditions. Anal. Bioanal. Chem 404, 1105–1112. doi: 10.1002/abbc.201100000

Wang, S., Wu, X. M., Liu, C. H., Shang, J. Y., Gao, F., and Guo, H. S. (2020). Verticillium dahliae chromatin remodeling facilitates the DNA damage repair in response to plant ROS stress. PLoS Pathog. 16e1008481. doi: 10.1371/journal.ppat.1008481

Wang, X., Liu, X., Chen, J., Han, H., and Yuan, Z. (2014). Evaluation and mechanism of antifungal effects of carbon nanomaterials in controlling...
plant fungal pathogen. *Carbon* 68, 798–806. doi: 10.1016/j.carbon.2013.11.072
Wang, X., Yang, X., Chen, S., Li, Q., Wang, W., Hou, C., et al. (2016). Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in Arabidopsis. *Front. Plant. Sci.* 6:1243. doi: 10.3389/fpls.2015.01243
Wang, Y., Jiang, F., Ma, C., Rui, Y., Xiang, D. C., and Xing, B. (2019). Effect of metal oxide nanoparticles on amino acids in wheat grains (*Triticum aestivum*) in a life cycle study. *J. Environ. Manage.* 241, 319–327. doi: 10.1016/j.jenvman.2019.04.041
Wang, Z., Xie, X., Zhao, J., Liu, X., Feng, W., White, J., C., et al. (2012). Xylem-and phloem-based transport of CuO nanoparticles in maize (*Zea mays L.*). *Environ. Sci. Technol.* 46, 4434–4441. doi: 10.1021/es202412x
Wani, A. H., and Shah, M. A. (2012). A unique and profound effect of MgO and ZnO nanoparticles on some plant pathogenic fungi. *J. Appl. Pharma. Sci.* 2:4.
Wild, E., and Jones, K. C. (2009). Novel method for the direct visualization of in vivo nanomaterials and chemical interactions in plants. *Environ. Sci. Technol.* 43, 5290–5294. doi: 10.1021/es900065b
Wilson, R. H., Nadeau, K. P., Jaworski, F. B., Tromberg, B. J., and Durkin, A. J. (2015). Review of short-wave infrared spectroscopy and imaging methods for biological tissue characterization. *J. Biomed. Optics.* 20:030901. doi: 11.1117/1.JBO.20.030901
Wojciechowsk, J., Jiménez-Lamana, J., Bierla, K., Asszemborska, M., Ruzik, L., Jarosz, M., et al. (2019). Elucidation of the fate of zinc in model plants using single particle ICP-MS and ESI tandem MS. *J. Anal. Atmos. Spectrom.* 34, 683–693. doi: 10.1039/C8JA00390D
Wolpert, S. G., Le, V., Verdouw, C., and Bogaardt, M. J. (2017). Big data in smart farming—a review. *Agricult. Syst.* 153, 69–80. doi: 10.1016/j.agsy.2017.01.023
Wong, M. H., Giraldo, J. P., Kwak, S. Y., Koman, V. B., Sinclair, R., Lew, T. T. S., et al. (2017). Nitroaromatic detection and infrared communication from wild-type plants using plant nanobions. *Nat. Mat.* 16, 264–272. doi: 10.1038/nmat4771
Wu, H., Santana, L., Dansie, J., and Giraldo, J. P. (2017a). In vivo delivery of nanoparticles into plant leaves. *Curr. Protoc. Chem. Biol.* 9, 289–284. doi: 10.1002/cphc.29
Wu, H., Shabala, S., Shabala, S., and Giraldo, J. P. (2018). Hydroxyl radical scavenging by cerium oxide nanoparticles improves arabidopsis salinity tolerance by enhancing leaf mesophyll potassium retention. *Environ. Sci. Nano* 5, 1567–1583. doi: 10.1039/C8EN00323H
Wu, H., Tito, N., and Giraldo, J. P. (2017b). Anionic cerium oxide nanoparticles protect plant photosynthesis from abiotic stress by scavenging reactive oxygen species. *ACS Nano* 11, 11283–11297. doi: 10.1021/acsnano.7b05723
Yan, A., and Chen, Z. (2019). Impacts of silver nanoparticles on plants: a focus on the phytotoxicity and underlying mechanism. *Int. J. Mol. Sci.* 20:1003. doi: 10.3390/ijms20051003
Yao, J., Yang, M., and Duan, Y. (2014). Chemistry, biology, and medicine of fluorescent nanomaterials and related systems: new insights into biosensing, bioimaging, genomics, diagnostics, and therapy. *Chem. Rev.* 114, 6130–6178. doi: 10.1021/cr200359p
Yao, K. S., Li, S. J., Treng, K. C., Cheng, T. C., Chang, C. Y., and Chiu, C. Y. (2009). Fluorescence silica nano probe as a biomarker for rapid detection of plant pathogens. *Adv. Mater. Sci. Eng.* 8, 1427–1436. doi: 10.1016/j.scitotenv.2006.11.007
Yosefi-Tanha, E., Fallah, S., Rostamnejadi, A., and Pokhrel, L. R. (2020). Particle size and concentration dependent toxicity of copper oxide nanoparticles (*CuONPs*) on seed yield and antioxidant defense system in soil grown soybean (*Glycine max cv. Kowarz*). *Sci. Total. Environ.* 715:136994. doi: 10.1016/j.scitotenv.2020.136994
Ze, Y., Liu, C., Wang, L., Hong, M., and Hong, F. (2011). The regulation of TiO 2 nanoparticles on the expression of light-harvesting complex II and photosynthesis of chloroplasts of *Arabidopsis thaliana*. *Biol. Trace. Elem. Res.* 143, 1131–1141. doi: 10.1007/s10521-010-8901-0
Zeng, Y., Himmel, M. E., and Ding, S. Y. (2017). Visualizing chemical functionality in plant cell walls. *Biotechnol. Biofuel.* 10, 1–16. doi: 10.1186/s13068-017-0973-3
Zhang, J., Landry, M. P., Barone, P. W., Kim, J. H., Lin, S., Ulissi, Z. W., et al. (2013). Molecular recognition using corona phase complexes made of synthetic polymers adsorbed on carbon nanotubes. *Nat. Nanotechnol.* 8, 959–968. doi: 10.1038/nnano.2013.236
Zhang, L., and Fang, M. (2010). Nanomaterials in pollution trace detection and environmental improvement. *Nano Today* 5, 128–142. doi: 10.1016/j.nanotoday.2010.03.002
Zhao, L., Hernandez-Viecas, J. A., Peralta-Videa, J. R., Bandyopadhyay, S., Peng, B., Munoz, B., et al. (2013a). ZnO nanoparticle fate in soil and zinc bioaccumulation in corn plants (*Zea mays*) influenced by alginates. *Envir. Sci. Proc. Impact.* 15, 260–266. doi: 10.1039/C2EM30610G
Zhao, L., Li, L., Wang, A., Zhang, H., Huang, M., Wu, H., et al. (2020). Nano-biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. *J. Agricul. Food. Chem.* 68, 1935–1947. doi: 10.1021/acs.jafc.9b06615
Zhao, L., Sun, Y., Hernandez-Viecas, J. A., Servin, A. D., Hong, J., Niu, G., et al. (2013b). Influence of CeO2 and ZnO nanoparticles on cucumber physiological markers and bioaccumulation of Ce and Zn: a life cycle study. *J. Agricul. Food. Chem.* 61, 11945–11951. doi: 10.1021/jf404328e
Zhu, H., Han, J., Xiao, J. Q., and Jin, Y. (2008). Uptake, translocation, and accumulation of manufactured iron oxide nanoparticles by pumpkin plants. *J. Environ. Monit.* 10, 713–717. doi: 10.1039/b80998e
Zhu, Z. J., Wang, H., Yan, B., Zheng, H., Jiang, Y., Miranda, O. R., et al. (2012). Effect of surface charge on the uptake and distribution of gold nanoparticles in four plant species. *Environ. Sci. Technol.* 46, 12391–12398. doi: 10.1021/es301977w

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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