Phytofabricated Metal Oxide Nanoparticles as Nano-Biostimulants for Salinity Stress Mitigation: Mechanisms, Agronomic Applications, and Translational Challenges

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Abstract: ***Soil salinization is one of the most widely distributed abiotic factors limiting global crop production. It encompasses over 833 million hectares of land in the world and is a major factor in food insecurity in arid, semi-arid and irrigated areas. Traditional salinity management practices – leaching, gypsum amendment, developing tolerant cultivars and chemical priming – are still only partial, slow and costly measures. In the past decade, phytofabricated (plant-mediated, "green") metal-oxide nanoparticles (MO-NPs) with the small-size reactivity of engineered nanomaterials (ENMs) and biocompatibility of the phytochemical capping agents have been developed as a new generation of nano-biostimulants. This review critically synthesizes knowledge on the effects of phytofabricated MO-NPs on reducing salinity stress in agronomically important crops. The chemistry of plant-extract mediated synthesis, advantages over the chemical and physical methods, and role of plant secondary metabolites (polyphenols, flavonoids, terpenoids and alkaloids) in particle stabilization and bioactivity is discussed. The mechanistic core includes six interconnected axes: (i) scavenging and modulation of reactive oxygen-species (ROS), (ii) restoration of Na^+/K^+ homeostasis through regulation of the SOS, NHX and HKT transporters, (iii) accumulation of osmoprotectants (proline, glycine betaine and soluble sugars), (iv) protection of the photosynthetic apparatus and membrane stability, (v) hormonal and nitric-oxide signalling, and (vi) nano-specific properties (nanozyme activity). We assess agronomic performance of wheat, maize, rice, soybean, tomato, barley and legumes – synergies with biochar, PGPR and arbuscular mycorrhizal fungi. Last, the concept of translational bottlenecks (dose-dependent phytotoxicity and soil-microbiome perturbation, environmental persistence, regulatory ambiguity, and scalability of phytofabrication) is introduced, and a forward agenda is proposed, focusing on multi-omics integration, field validation, smart delivery, and AI-guided synthesis. However, the use of Phytofabricated MO-NPs in salinity management has enormous potential but needs to be backed by evidence-based deployment of crop-specific and ecologically informed use.***

Keywords: Phytofabrication; green synthesis; metal oxide nanoparticles; salinity stress; nano-biostimulants; ROS scavenging; ion homeostasis; antioxidant enzymes; sustainable agriculture; nanotoxicity

1. Introduction

Salinization is one of the most significant and rapidly spreading types of land degradation, affecting the world's agricultural production and food security. According to the last global evaluation of salt-affected soils by the Food and Agriculture Organization (FAO), over 833 million hectares, or about 8.7 % of the Earth's lands, are affected by salinity, and are growing by around 1.5 million hectares a year as a result of an interplay of climatic and anthropogenic factors (Bose & Pal, 2025; Shahid et al., 2018). The secondary salinization is a recurring hazard for civilization since the Mesopotamian region; however, current developments such as the use of brackish water and the rise in sea level, the reduction of rain in semi-arid regions, and the overuse of synthetic fertilizers have led to an unprecedented loss of arable land (Zaman et al., 2016; Hossain et al., 2020). With no effective action, up to 50 % of all arable land was projected to be impacted by salinity by mid-century (Butcher et al., 2016).

Plants are subjected to a double stress (osmotic and ionic) by salinity. The osmotic component causes almost instantaneous water uptake, reducing the soil water potential, whereas the ionic component, caused by the progressive accumulation of Na^+ and Cl^- in the cytosol, impacts enzyme activity, photosynthetic electron transport and ion homeostasis (Li et al., 2022). All these stressors produce high levels of Reactive Oxygen Species (ROS) in chloroplasts, mitochondria and peroxisomes, resulting in lipid peroxidation, membrane disorganization, protein carbonylation, and DNA damage (Singh et al., 2025). The impact downstream on crop physiology is significant: from degradation of chlorophyll, stomatal closure, decrease in photosynthetic efficiency, imbalance in hormones, to changes in root structure and considerable yield loss (up to 20-60 % in moderate saline soils and up to 100 % in extreme conditions (Adil et al., 2022; Mazhar et al., 2023). Cereals like rice and wheat, vegetables like tomato, and oilseeds like soybean, in particular, are sensitive, but there is also substantial inter- and intraspecific variability (Aazami et al., 2021; Abdelhameed et al., 2025a).

The traditional methods of salinity management (leaching with good quality water, addition of gypsum, organic amendments, drainage implementation and genetic selection of salinity-tolerant cultivars) have proven to be very inconsistent and sometimes too expensive to be implemented on a commercial scale, especially by smallholder farmers in arid and semi-arid areas. The multigenic and complicated nature of salt tolerance has hindered plant breeding, and the partial loss of tolerance traits in elite genotypes (Abdelhameed et al., 2025a). The use of plant biostimulants, which are biological products or microorganisms used to improve nutrition efficiency, abiotic stress and crop quality, has become a complementary and more sustainable approach (Bahuguna et al., 2022). In this growing biostimulant landscape, nanotechnology has emerged as a unique approach by engineering "nano-biostimulants" with specific surface chemistry, reactivity and increased uptake caused by the small size and dimensions of the nanomaterials, which provide stress-mitigating properties at concentrations orders of magnitude lower than the bulk equivalents (Chittibomma et al., 2023; Li et al., 2022).

In particular, metal-oxide nanoparticles (MO-NPs) like ZnO, Fe_2O_3/Fe_3O_4, TiO_2, MgO, CuO, SiO_2, and CeO_2 have been gaining attention in their connection with agriculture. The ability to withstand stress is enhanced by these oxides, which simultaneously possess the nutrient functions of the constituent elements, in addition to possessing strong redox, catalytic and surface-adsorption properties that can directly influence ROS, ion homeostasis and signalling under stress (Singh et al., 2025; Anand & Arora, 2026). The traditional chemical and physical pathways for the synthesis of MO-NPs, however, do not align with the desire to make agricultural production more sustainable, as they use toxic reductants, high temperatures, and energy-intensive processing, and they pose concerns about the presence of residual contaminants. Therefore, the most promising green-chemistry method for MO-NPs suitable for agricultural applications is the so-called phytofabrication (Sangeetha et al., 2011; Mogazy & Hanafy, 2022; Roy et al., 2025), which uses water-based extracts of plant materials as reducing, capping, and stabilizing agents. Bioactivity is added to particles formed this way through the phytochemical corona, which consists of compounds present in the source extract that can also be antioxidants and signalling molecules, creating what has been called a "double biostimulant effect" (Ashraf et al., 2025; Abdelhameed et al., 2025a).

Since 2020, the number of studies conducting MO-NPs production by plants for salinity-stress mitigation has increased rapidly. Recent landmark studies have shown that the green-synthesized ZnO NPs using *Mentha spicata* extract restored growth and yield of *Vicia faba* under salinity (Mogazy & Hanafy, 2022), CuO NPs using *Sargassum species* restored the ionic homeostasis and antioxidant defense in salt-stressed maize (Ashraf et al., 2025), TiO_2 NPs using *Mentha spicata* and *Solenostemma argel* restored growth and yield in salt-stressed soybean and bean (Abdelhameed et al., 2025a; Abdelhameed et al., 2025b; Abdalla et al., 2022), and CuO NPs using *Moringa oleifera*, *Mentha spicata,* and *Solenostemma argel* alleviated stress in tomato and barley (El-Tanbouly et al., 2025; EL-Messeiry et al., 2026; Shaikhaldein et al., 2024). Concurrently, it has been demonstrated that nano-specific properties including nanozyme activity (SOD/CAT/peroxidase), foliar penetration, controlled release of metal ions and modulation of NO and hormonal signalling mechanisms are not available for bulk equivalents (Wu et al., 2025; Niyazi et al., 2026; Kolbert et al., 2021).

However, the momentum has not yet had a significant impact on the field, which remains divided. The vast majority of published studies have been performed under controlled-pot or hydroponic settings, and there have been only a few successful field-scale validations, and there is a lack of consistency among the particle characterization, dose and exposure route. There have been repeated reports of contradictions between studies, dose-dependent phytotoxicity at higher concentrations, gaps in understanding the fate of nanotechnology materials after long-term application in soil and plants, and the lack of harmonized regulatory structure for agricultural nanotechnology materials (Yang et al., 2017; Wang et al., 2023; Chittibomma et al., 2023). Moreover, it is often difficult to separate the true contribution of the phytochemical corona from that of the metal-oxide core itself, and it is still not known if the "green" property is necessary for the metal-oxide core alone or whether it is a result of the phytochemical corona. This review addresses these issues by providing a critical, evidence-based synthesis of phytofabricated MO-NPs as nano-biostimulants for salinity stress mitigation.

2. Phytofabricated Metal Oxide Nanoparticles: Synthesis, Advantages, and Characterization

2.1 Principles of Phytofabrication

The reducing, chelating and capping properties of plant secondary metabolites is used to reduce metal salts under ambient conditions at low temperature in the aqueous phase, a process called phytofabrication, or green synthesis, or plant-mediated synthesis. The pioneering demonstration by Sangeetha and co-workers (2011) using the extract of the leaf of *Aloe barbadensis Miller* to transform zinc nitrate into well crystalline hexagonal ZnO nanoparticles using the techniques of FTIR, SEM, TEM and XRD set the conceptual and methodological foundation for the field (Sangeetha et al., 2011). In a typical procedure, the fresh plant materials are extracted with water (by maceration or hot water extraction) and a metal precursor such as $Zn(NO_3)_2$, $FeCl_3$, $TiO(OH)_2$, $MgCl_2$, $CuSO_4$, etc. is added to the extract, the mixture is stirred and heated slightly, and the precipitate is calcined at 300-500 °C to get the crystalline oxide. The polyphenols, flavonoids, terpenoids, alkaloids, organic acids and proteins in the extract transfer electrons to the metal ions to reduce the metal ions and functional groups like –OH, –COOH, –C=O chelate the newly formed clusters and help in preventing their aggregation (Sangeetha et al., 2011; Rashid et al., 2024). It requires no hazardous reductants (NaBH4, hydrazine), strong surfactants (CTAB), or high energy processing usually used in conventional chemical synthesis, and it can be done at ambient temperature.

Plant species have a large effect on particle size, shape, crystallinity, and surface chemistry as each plant produces a unique phytochemical fingerprint. The high concentration of polysaccharides and anthraquinones in aloe vera gel has synthesized Zinc Oxide (ZnO) and Cu doped ZnO (CZO) nanoparticles of 25–40 nm size with quasi-spherical shape and their enhanced antibacterial and photocatalytic activity (Sangeetha et al., 2011; Rashid et al., 2024). Under salinity, spraying of the growth of broad bean plants with ZnO NPs prepared from *Mentha spicata* extract significantly enhanced the growth, antioxidants enzyme and chlorophyll. Spraying of the broad bean growth with zinc oxide nanoparticles from *M. spicata* extract under salinity significantly enhanced growth, antioxidants enzyme and chlorophyll activities (Mogazy &

Hanafy, 2022). The alga *Sargassum* is being used as a proxy plant system, from which ZnO NPs have been provided that enhance ion homeostasis in maize under salinity (Ashraf et al., 2025). *Mentha spicata, Moringa oleifera, Melia azedarach*, and *Solenostemma argel* extracts have been used to develop CuO NPs that have been applied to tackle salinity, drought, and metal stress in tomato, wheat, and barley (EL-Messeiry et al., 2026; El-Tanbouly et al., 2025; Naz et al., 2025; Shaikhaldein et al., 2024). The TiO_2 NPs developed by the Abdalla/Hegazy lab have been evaluated in various crops such as bean, soybean and wheat (Abdalla et al., 2022; Abdelhameed et al., 2025a; Abdelhameed et al., 2025b). SiO_2 is the most interesting example of valorising rice-husk biomass to a stress-mitigating nanomaterial, as the biogenic silicon nanoparticles (SiNPs) were recovered from a biomass source and exhibit stress-mitigating properties (Gonc et al., 2024; Siddiqi et al., 2025).

2.2 Advantages over Chemical and Physical Synthesis

The benefits of phytofabrication over chemical and physical techniques have been reported previously. The elimination of toxic reductants and organic solvents greatly decreases the environmental impact and make the resulting NPs more appropriate for use in food crops applications (Chittibomma et al., 2023; Mogazy & Hanafy, 2022). Second, the phytochemical corona that is adsorbed to the surface of the particle has intrinsic biological activity, polyphenols and flavonoids that remain on the surface can exert antioxidant activity and also can participate in ROS scavenging when reaching the plants (Amir et al., 2024; Ashraf et al., 2025). Third, the reaction conditions are energetic (no need for high temperatures; normal water). Fourth, some phytofabricated MO-NPs perform better in terms of colloidal stability in plant-treatment solutions, thereby preventing premature aggregation in foliar and in root-zone applications, respectively (Singh et al., 2025; Roy et al., 2025).

Nevertheless, there are real constraints with phytofabrication. However, there are challenges of batch to batch variations in composition of the extract because of seasonal, geographical and post-harvest factors, which make it difficult to achieve reproducibility. There is not a good example of how to go from laboratory scale batches (usually 50–500 mL) to agronomically meaningful quantities. The size and morphology distributions is broader than chemically synthesized counterparts. The removal of organic residues during calcination can inadvertently remove the same organic shell detected as associated with biostimulatory activity, causing confusion in terms of the type of active principle, either the oxide core or the organic residue (Wang et al., 2023; Yang et al., 2017). These limitations confirm that although the phytofabrication is the most sustainable synthesis pathway, the methodology has to be matured for promotion in the field.

2.3 Characterization, Halophyte-Based Syntheses, and Scalability

For translational deployment, robust characterization is a must. The battery of minimum recommended tests contains UV-Vis spectroscopy (for detection of surface plasmon or band-edge transitions), XRD (for crystallinity and phase identification), FTIR (for identification of capping functional groups), DLS and zeta potential (hydrodynamic size and colloidal stability) and electron microscopy (SEM/TEM) (for morphology and primary size) (Sangeetha et al., 2011; Rashid et al., 2024; Mogazy & Hanafy, 2022; Adil et al., 2022). Recent best-practice studies also involve the use of EDX, BET surface area and thermal-gravimetric analysis (TGA) to detect the presence of residual organics (Khan et al., 2026).

One particularly interesting development is the use of extracts of halophytes such as *Salicornia, Suaeda* and *Sarcocornia* as well as *Atriplex*, whose secondary metabolites are themselves the products of evolutionary adaptation to salinity and which may impart specific salt-mitigating properties to the resulting particles. Halophyte extracts have been used as biocidal and reducing agents in several studies (Atzori et al., 2025) and have been combined with selenium nanoparticles and methyl jasmonate in salinity-stressed *Sarcocornia* shoot cultures (Salem et al., 2025). While the superiority of halophyte MO-NPs over the mesophyte equivalents under salinity has not yet been demonstrated directly, their concept based on the pre-adaptive ability of the corona of the phytochemicals derived from the halophytes (glycine betaine precursors, polyamines, polyphenols) to deal with ionic and osmotic stress has sparked a surge in interest (Székely & Barta, 2025).

The most pressing issue for translation is scalability. Most of the published phytofabrication procedures produce sub-gram quantities. Pilot-scale flow reactors and continuous-extraction systems are being considered, but production standardisation for agricultural-grade phytofabricated MO-NPs is almost non-existent (Chittibomma et al., 2023; Ajanaku et al., 2025). This lack of standardization makes it difficult to compare the results of studies and makes it virtually impossible to obtain regulatory approval.

3. Mechanisms of Action as Nano-Biostimulants under Salinity Stress

There are numerous multi-axial mechanisms proposed for salinity stress mitigation by phytofabricated MO-NPs, with their relative weights varying with the type of particle, dosage, plant species, growth stage, exposure route and salinity stress severity. We talk about six interlocking axes most of which account for most reported effects.

3.1 ROS Scavenging and Antioxidant Enzyme Modulation

Salinity induced physiological reaction is most consistently reported to be ROS overproduction, being mainly in chloroplasts (in PSI/PSII and photorespiration) and mitochondria and peroxisomes (Singh et al., 2025; Anand & Arora, 2026). The unchecked ROS initiate lipid peroxidation (malondialdehyde, MDA), protein carbonylation and DNA damage, which result in impaired membrane stability and metabolic function. Plants respond to this with enzymatic antioxidants (superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione peroxidase (GPX) and ascorbate–glutathione (AsA-GSH) cycle) and non-enzymatic antioxidants (ascorbate, glutathione, phenolics, carotenoids and tocopherols).

The enzymatic antioxidants are always upregulated and the accumulation of MDA is always lowered in the case of phytofabricated MO-NPs. Mishra et al., (2025) found that green synthesized ZnO NPs greatly improved the activity of SOD, POD, APX and CAT in salt stressed rice and also reduced the stress markers. Mogazy and Hanafy (2022) reported similar enhancement in the activities of CAT and APX with a significant decrease in the oxidative damage parameters in Vicia faba when ZnO NPs were synthesized using *Mentha spicata* (Mogazy & Hanafy, 2022). Aazami et al. (2021) found coordinated upregulation of SOD, APX and CAT genes in tomato crop in salinity stress conditions, but cultivar specific response was observed (Aazami et al., 2021), especially in "Roma" cultivar (Aazami et al., 2021). Under salt stress, foliar ZnO NPs in sunflower resulted in a rise in the antioxidant activities of SOD and APX, which is one of the basic proof of antioxidant-modulation effect (Torabian et al., 2018). Phytofabricated gold NPs successfully applied to spinach subjected to salinity stress also increased the antioxidant modulating capacity, which confirms that the antioxidant-modulating capacity is not limited to metal-oxide systems (Amir et al., 2024).

In addition to enzymatic upregulation, some of the MO-NPs possess intrinsic multivalent "nanozyme" activity, such as the ability to mimic SOD, CAT and peroxidase (e.g., CeO_2, Mn-doped CeO_2; Niyazi et al., 2026; Wu et al., 2025). Under cold stress, Mn-doped CeO_2 nanozymes have been reported to be involved in ROS homeostasis and in shifts in the metabolic network of hormones to facilitate wheat germination (Wu et al., 2025); foliar application of CeO_2 nanomaterials under salinity stress has been reported to improve maize yield by mitigating ROS and altering the rhizobacterial community structure (Liu et al., 2022). Niyazi et al. (2026) specifically put forward CeO_2 nanozymes as redox regulators which modulate ROS signalling for plant climate resilience (Niyazi et al., 2026). CeO_2 is not reported as a strict "phytofabricated" system, but its nanozyme principle is being increasingly adopted in phytofabricated systems with the addition of complementary radical-scavenging properties of the phytochemical corona.

3.2 Ion Homeostasis: Na^+/K^+, SOS, NHX, and HKT Regulation

Na^+/K^+ homeostasis is a key feature of salinity stress. Na^+ enters the cells either via non-selective cation channels or via HKT transporters and if not pumped out of the cell by plasma-membrane Na^+/H^+ antiporters (SOS1), it is sequestered into vacuoles by tonoplast antiporters (NHX1/2) and can inhibit enzymes and other K^+ dependent processes in the cytoplasm (Li et al., 2022; Gholizadeh et al., 2025). The Salt Overly Sensitive (SOS) pathway (Ca^{2+}-sensor SOS3, kinase SOS2 and antiporter SOS1) controls the efflux of ions, the HKT transporters, which transport Na^+ from the xylem, limit shoot loading.

This network has been found to be favourably modulated by repeatedly using MO-NPs phytofabricated and green-synthesized. Under salinity stress conditions, the study of biogenic TiO_2 NPs in soybean by Abdelhameed et al. (2025b) showed that the balance of K^+/Na^+ was maintained and the MDA content was reduced, with the term "maintaining proper ion balance" highlighted as a mechanistic axis (Abdelhameed et al., 2025b). The integrative nano-platform of chitosan-proline and chitosan-glycine NPs also led to a decrease in cytosolic Na^+ by regulating the expression of NHX and HKT genes, which is consistent with the overall finding that NP tolerance to salt stress is often linked to the direct or indirect regulation of these transporters (Gholizadeh et al., 2025). Anand and Arora (2026) specifically mention the ability of nanoparticles to "precisely target the SOS pathway, NHX vacuolar sequestration, and HKT xylem unloading" (Anand & Arora, 2026). Ashraf et al. (2025) reported that the application of *Sargassum* synthesized ZnO NPs ameliorated salinity-induced ionic and osmotic homeostasis disruption in maize (Ashraf et al., 2025), and Akter et al. (2025) reported that the application of MgO NPs in soybean caused ionic and osmotic regulation to reduce salinity-induced disruption in physiological processes (Akter et al., 2025). ZnO NPs in combination with plant growth-promoting rhizobacteria (PGPR) showed significant effects on improving the K^+/Na^+ ratio in wheat under sodic-saline soil in the field-scale study conducted by Alharbi et al. (2023). Similarly, the abilities to enhance K^+/Na^+ homeostasis have been reported in salt-stressed barley under biosynthesized Cu NPs from *Solenostemma argel*, which further indicates that the improvement in K^+/Na^+ homeostasis is not exclusive to the ZnO and Fe systems (Shaikhaldein et al., 2024).

Mechanistically, MO-NPs are believed to affect the ion homeostasis in the plant via four possible pathways: (i) direct delivery of beneficial nutrients (Zn^{2+}, Mg^{2+}, $Fe^{2+/3+}$, Si) that compete with Na^+ at the root surface; (ii) up-regulation of SOS-pathway and NHX/HKT gene expression by changing Ca^{2+} and ROS signalling; and (iii) reinforcement of root apoplastic barriers through Si deposition, thereby reducing transpirational Na^+ loading; (iv) modulation of plasma-membrane H^+-ATPase activity that drives SOS1-mediated Na^+ pumping from the cell.

3.3 Osmoprotectant Accumulation: Proline, Glycine Betaine, and Soluble Sugars

Compatible solutes (proline, glycine betaine, soluble sugars, polyols) stabilize protein structure, scavenge ·OH and maintain cellular turgor under osmotic stress. MO-NPs often affect the levels of compatible solutes, but the direction of the changes depends on the stress levels of the stressed-only controls. Under salinity, Mishra et al. (2025) reported that the trajectory of proline in rice changed after Se/ZnO NP treatment along with an improvement in the balance of antioxidant enzymes (Mishra et al., 2025). The use of Zn nanoparticles along with proline exogenous application had an osmoprotective effect and showed improvement in growth, physiological parameters, and yield in pea (*Pisum sativum*) seeds when grown in diluted seawater (El-Beltagi et al., 2024). It is a particularly elegant convergence of nanotechnology with osmoprotectant chemistry: glycine-betaine functionalized ZnO NPs (Singh et al., 2026) alleviated salinity in *Vigna radiata* by coupled regulation of the osmotic, ionic and antioxidant pool, thereby increasing endogenous glycine betaine and proline pool. The application of ZnO NPs coupled with PGPR reduced leaf proline compared to saline water stressed plants, and had a positive effect on plant growth without increasing the level of plant osmotic adjustment (Alharbi et al., 2023). These observations serve as an important interpretative reminder that increasing the proline level during stress is not necessarily a good thing; the question is whether or not NP treatment is able to establish a healthier proline trajectory that aligns with improvements in growth and yield, not just with increased proline levels.

3.4 Photosynthetic Efficiency, Chlorophyll, and Membrane Stability

Mechanisms of salinity effects on photosynthesis include stomatal closure, increased chlorophyll breakdown, photoinhibition of PSII, and thylakoid membrane disorganization. Typical indicators of photosynthesis are restored in most cases by use of Phytofabricated MO-NPs. Adil et al., (2022) showed the potential of ZnO NPs to enhance the content of chlorophyll a and b, plant height and grain yield in wheat under salt stress condition when administered at appropriate doses (Adil et al., 2022). Under salinity, Khan et al. (2026) found that the synergistic effects of green-synthesized ZnO NPs and walnut biochar restored the membrane integrity, gas-exchange parameters and chlorophyll content of maize plants. Kreslavski et al. (2023) demonstrated that the photosynthetic decline caused by salinity stress in wheat was counteracted by Fe_3O_4 NPs, which enhanced chlorophyll, electron transport, and mineral distribution in wheat (Kreslavski et al., 2023). In a saline stressed *Zea mays*, Iheme et al. (2024) reported a measurable recovery of photosynthetic indices and antioxidant enzyme activity was achieved in the presence of iron-oxide NPs (Iheme et al., 2024). In beans, *Funneliformis mosseae* with TiO_2 NPs increased salinities tolerance up to approximately 110 % at the highest tested concentration (El-Gazzar et al., 2020) and in soybean, biogenic TiO_2 NPs resulted in higher chlorophyll content and gas exchange and lower MDA levels (Abdelhameed et al., 2025b). For strawberry under salinity and alkalinity, GO NPs increased the gas exchange and photosynthetic efficiency, which served as a comparison reference material of carbon-nanomaterial (Malekzadeh et al., 2023).

A special mention here should be made for silicon nanoparticles. Alam et al. (2022) found that SiNPs effectively restored carbohydrate metabolism, photosynthesis and ROS homeostasis in salt-stressed tomato (*Solanum lycopersicum*), whereas Mukarram et al. (2023) showed that SiNPs restored photosynthesis and essential-oil content in salinity-stressed lemongrass through upregulation of antioxidant metabolism (Mukarram et al., 2023). Liang et al. (2023) demonstrated the ability for SiNPs to keep maintaining photosynthetic activity in cotton subjected to simultaneous salt and cold stress (Liang et al., 2023). The results together demonstrate a strong and repeatable MO-NP mediated signature of photosynthetic restoration for salinity mitigation.

3.5 Hormonal Regulation, Nitric Oxide, and Signalling

The plant's hormone levels get disrupted due to salinity: ABA increases significantly, JA and ethylene are induced, and growth promoting hormones (IAA, GA, CK) usually decrease. The relationship between MO-NPs and this hormonal situation is now being mapped. NO, among others, has proved to be an important intermediate. Studies conducted by Oliveira et al. (2016) provided the basic evidence that NO-releasing chitosan NPs mitigate salt stress in maize via improved plant physiology (Oliveira et al., 2016), and Seabra et al. (2022) reviewed how NO-releasing nanomaterials can be used in agriculture (Seabra et al., 2022). In the context of plant nanobiology, Kolbert et al. (2021) systematically reviewed the role of NO both as an inducer and modulator of stress responses, with NPs playing both roles (Kolbert et al., 2021). NO, not only acts as a signal in downstream of NP exposure but also protects against excess NP-induced ROS, as shown by Tripathi et al. (2017) in wheat. Under abiotic stress conditions, Tripathi et al. (2023) also explained the interaction between polyamines and NO that can be controlled by nanoparticles (Tripathi et al., 2023). Under stress, the CeO_2 nanozymes directly interact with the auxin and gibberellin pathways in the metabolic networks of hormones in wheat to enhance germination, as reported by Wu et al. (2025).

Evidence for ABA and JA is circumstantial but is coming together. Physiological recovery has been reported with changes in stress hormone biosynthesis genes or changes in endogenous ABA pools in several phytofabricated MO-NP studies (Abdelhameed et al., 2025a; Abdelhameed et al., 2025b; EL-Messeiry et al., 2026). Anand and Arora (2026) highlight that hormones-signalling genes are among the various genes to which NPs bind and regulate, but the exact sequence in which they bind and regulate differs across systems. The work by Methela et al. (2023) complemented this with evidence that chitosan-GSNO NPs are positive modulators of drought-stress tolerance in soybean that could be easily extrapolated conceptually to salinity (Methela et al., 2023). The idea of coupling MO-NPs with conventional nanotechnology is therefore a current research area.

3.6 Nano-Specific Effects: Nanozyme Activity, Uptake, Translocation, and Root–Leaf Interfaces

There are several mechanisms that are very peculiar to the nano scale and can't be simply scaled up to the bulk scale. In contrast to the fully induced enzymatic antioxidants, intrinsic nanozyme activity (CeO_2, Fe_3O_4 in surface-defect-rich state and slightly ZnO and TiO_2) allows to catalyse superoxide and break down H_2O_2 at the site of its generation, without relying on enzymes pre-induced by external stimuli (Wu et al., 2025; Niyazi et al., 2026). The small size of phyto-MO-NPs, typically 20-80 nm, allows for their effective delivery through low-cost foliar sprays, which involves foliar uptake by stomatal and cuticular pathways (Mogazy & Hanafy, 2022; Adil et al., 2022; Amir et al., 2024). The internalization of NPs can be facilitated by the secondary phytochemical corona and influenced by the particle size, surface charge (zeta potential); after uptake, NPs migrate from the cell wall continuum apoplastically and from the cell wall to the cytoplasm via plasmodesmata and then enter the transpiration stream to translocate to shoots (Yang et al., 2017; Wang et al., 2023). Importantly, the phytochemical corona can mediate plant–NP recognition: corona components, such as polyphenols, may engage flavonoid receptors, and reactive carbonyl-scavenging pathways can be elucidated, thus bringing biological context to the otherwise abiotic core (Ashraf et al., 2025; Singh et al., 2026).

The observation made throughout the literature is that all these effects are very dose-dependent. Sub-optimal concentrations under-perform, optimal concentrations increase tolerance to stress and supra-optimal concentrations produce phytotoxicity, which is generally worse than the salinity stress itself. The reported optimum foliar concentrations of phytofabricated ZnO NPs against salinity ranged from 25 to 100 mg L^{-1}, but could differ significantly based on the crop and exposure treatment (Mogazy & Hanafy, 2022; Mishra et al., 2025; Adil et al., 2022). A safe range (25–50 mg L^{-1}) has been developed for CuO NPs in barley and tomato (Shaikhaldein et al., 2024; EL-Messeiry et al., 2026). For Fe_3O_4 and TiO_2 systems, optimum windows of 50–100 mg L^{-1} or 30–60 mg L^{-1} are commonly reported (Kreslavski et al., 2023; Abdelhameed et al., 2025b; Mukhtiar et al., 2024). Such windows are only suggestive and over extrapolation between studies is a significant risk.

Table 1: Representative phytofabricated/green-synthesized metal-oxide nanoparticle studies on salinity mitigation: plant extract, NP type, dose, target crop, and key outcomes

Phytofabrication source	NP type	Dose	Crop / system	Salinity level	Key outcomes	Reference
Mentha spicata	ZnO	25–100 mg L^{-1} foliar	*Vicia faba*	100–200 mM NaCl	Restored growth, chlorophyll; ↑ SOD/CAT/APX; ↓ MDA	Mogazy & Hanafy (2022)
Sargassum	ZnO	Foliar	*Zea mays*	NaCl	Improved ion homeostasis; ↑ antioxidants	Ashraf et al. (2025)
Green-synth ZnO + walnut biochar	ZnO + BC	Combined soil treatment	*Zea mays*	NaCl	Synergistic mitigation; improved physiology	Khan et al. (2026)
Green-synth TiO_2	TiO_2	Foliar	*Glycine max*	NaCl	Modulated metabolic constituents; reduced damage	Abdelhameed et al. (2025a)
Biogenic TiO_2	TiO_2	Foliar	*Glycine max*	NaCl	Ion homeostasis; ↓ MDA	Abdelhameed et al. (2025b)
Green-synth TiO_2	TiO_2	Seed/soil	Soybean	Stress	↑ Seedling emergence, vigor, DPPH	Abdalla et al. (2022)
F. mosseae + TiO_2	TiO_2	Combined	*Phaseolus vulgaris*	NaCl	Up to 110 % tolerance enhancement	El-Gazzar et al. (2020)
Mentha spicata	CuNPs	Foliar	*Solanum lycopersicum*	NaCl	Physiological/gene-expression improvements	EL-Messeiry et al. (2026)
Solenostemma argel	Cu NPs	25–50 mg L^{-1}	*Hordeum vulgare*	NaCl	Mitigated salt stress; ↑ growth	Shaikhaldein et al. (2024)
Moringa oleifera	CuO NPs	Foliar	*Solanum lycopersicum*	Drought	Increased osmoprotectants; ↑ chlorophyll	El-Tanbouly et al. (2025)
ZnO/MgO bimetallic	ZnO/MgO	Foliar/soil	Cucumber/other	Seawater stress	Biostimulant; antibacterial	Selim et al. (2025)
MgO NPs	MgO	Foliar	*Glycine max*	NaCl	Alleviated physiological/ biochemical disruption	Akter et al. (2025)
Rice-husk biogenic Si	nano-Si	Seed/foliar	*H. vulgare, Triticum*	Salinity + B	Improved tolerance, growth	Gonc et al. (2024)
SiO_2 NPs + AMF/PGPR	SiO_2	Combined	NaCl	NaCl	Improved nutrient uptake, antioxidants	Ahmadi-Nouraldinvand et al. (2024)
Foliar CeO_2	CeO_2	Foliar	*Zea mays*	NaCl	↑ Yield; ROS regulation; rhizobacterial shifts	Liu et al. (2022)
Mn-doped CeO_2 nanozyme	CeO_2	Seed	*Triticum*	Low temp	ROS/hormone modulation	Wu et al. (2025)
Aqueous extract + green ZnO	ZnO	Foliar	*Oryza sativa*	NaCl	Improved yield, antioxidants	Mishra et al. (2025)

4. Agronomic Applications and Efficacy

4.1 Cereals: Wheat, Rice, and Maize

Wheat (*Triticum aestivum*) has been the most broadly researched cereal for MO-NP mediated salinity mitigation, largely due to its world-wide importance as a staple cereal and moderate sensitivity to salinity. Adil et al. (2022) showed that foliar application of ZnO NPs significantly increased the yield parameters, physical characteristics, and chlorophyll content in wheat under salinity stress with the best concentration of ZnO NPs showing the maximum effect compared to the salinity stress control. Adil et al. (2022) found that the yield parameters, physical characteristics and chlorophyll content of wheat plants increased significantly in response to foliar application of ZnO NPs, with maximum effect observed under the optimal concentration of ZnO NPs compared to control plants under salinity stress conditions. In an open field experiment conducted by Alharbi et al. (2023) in Kafr El-Sheikh, Egypt, the use of ZnO NPs in combination with PGPR resulted in high levels of K^+/Na^+ ratio, growth and productivity under saline-water irrigation in sodic-saline soils (Alharbi et al., 2023). The yield of wheat crop and physical soil properties were also enhanced under soil salinity and sodicity conditions by the application of ZnO NPs along with soil amendments, which was reported by El-Sharkawy et al. (2022). Mazhar et al. (2023) extended the above conclusion to the case of grain zinc fortification, showing that application of ZnO NP not only reduced the effects of salt stress, but also enhanced the partitioning of zinc in wheat and rice grain—a remarkable overlap in the objectives of abiotic stress tolerance and biofortification (Mazhar et al., 2023). In arid sandy saline soils, a multi-component nano-formulation of k-humate, proline and Si/Zn NPs is used to overcome two or more physiological bottlenecks, as illustrated by the integrated nano-platform of Abd-Elzaher et al. (2022) (Abd-Elzaher et al., 2022). Kreslavski et al. (2023) reported enhanced chlorophyll, photosynthesis, and antioxidants defence in salt-stressed wheat with Fe_3O_4 NPs while Mukhtiar et al. (2024) found that Fe_3O_4 NPs were more effective than other Fe sources in salt-stressed maize in all the parameters measured (Mukhtiar et al., 2024). Alsamadany et al. (2024) reported residual efficiency of FeNPs and other Fe sources throughout the life cycle of maize (Alsamadany et al., 2024).

Rice (*Oryza sativa*) has been gaining more and more attention, especially in saline-deltaic systems in Asia. Mishra et al. (2025) demonstrated that the synergistic effects of green-synthesized Se- and ZnO-NPs were highly effective in reducing yield losses under salt stress in rice and led to co-ordinated enhancement of antioxidant enzymes and grain yield (Mishra et al., 2025). Maize is a moderately sensitive crop and is globally significant, which has led to an abundance of maize studies. As per the study of Ashraf et al. (2025), the induction of salt tolerance in maize with the help of *Sargassum*-derived ZnO NPs was highlighted by the improvement of physiological and biochemical mechanisms in the plants (Ashraf et al., 2025). Similar effects are also reported by Iheme et al. (2024) and Mukhtiar et al. (2024) in their studies with iron-oxide NPs (Iheme et al., 2024; Mukhtiar et al., 2024). Abdulfatah et al. (2025) showed that green synthesized FeNPs enhanced seed germination of maize in salinity stress, benefitting the plants at an early stage which could increase stand establishment at the field level (Abdulfatah et al., 2025). Liu et al. (2022) reported that coupled ROS homeostasis and rhizobacterial community modulation via foliar application of CeO_2 nanomaterials enhanced maize yield under salinity stress (Liu et al., 2022). The use of green-synthesized ZnO NPs in combination with walnut biochar has been demonstrated to be more effective than either intervention alone in restoring physiology and growth under saline soil conditions in maize by Khan et al. (2026).

4.2 Legumes and Oilseeds: Soybean, Broad Bean, Pea, Barley

There has been a large amount of research on the responses of legumes and oilseed crops to salinity conditions in the presence of phytofabricated MO-NPs. As an exemplary, M. Mogazy and Hanafy (2022) found that foliar application of ZnO NPs in Vicia faba caused an alleviation of the salinity-induced damage that resulted in restoration of growth and antioxidant balance (Mogazy & Hanafy, 2022). Three major studies conducted by the Abdelhameed/Hegazy lab established that three metabolic constituents, cell ultrastructure, ion homeostasis, and overall salinity tolerance are enhanced by green-synthesized TiO_2 NPs in soybean (Glycine max) (Abdalla et al., 2022; Abdelhameed et al., 2025a; Abdelhameed et al., 2025b). Akter et al. (2025) found that soybean productivity was improved under salinity stresses using MgO NPs, which minimized the physiological and biochemical disruption (Akter et al., 2025). Urea–phosphate combined with MgO NPs enhanced productivity of soybean in saline-sodic soils by reducing the physiological and biochemical disturbances, which was demonstrated by Abou-Zaid et al. (2025) (Abou-Zaid et al., 2025). Rashidpour et al. (2025) applied the MgO concept to sesame, demonstrating synergism of metabolites under different water regimes with mycorrhizal fungi (Rashidpour et al., 2025).

El-Beltagi et al. (2024) found that, in pea (*Pisum sativum*) under diluted seawater irrigation, the use of zinc NPs along with exogenous proline resulted in better growth, physiology and yield (El-Beltagi et al., 2024). Shaikhaldein et al. (2024) reported that Cu NPs synthesized using *Solenostemma argel* were able to improve plant growth under salt stress when applied at a specific concentration range (25-50 mg L-1) in barley (*Hordeum vulgare*) (Shaikhaldein et al., 2024). Gholizadeh et al. (2026) also reported that the enhancement of salt-stress tolerance in barley by the application of chitosan-selenium nanoparticles was attributed to changes in the expression of the HKT, SOS, TVP and NHX gene families (Gholizadeh et al., 2026). The combined boron + salinity stress tolerance of both barley and wheat was enhanced by biogenic nano-silicon derived from rice husk, as demonstrated by Gonc et al. (2024) (Gonc et al., 2024).

4.3 Vegetables and Horticultural Crops: Tomato, Cucumber, Radish, Spinach, Strawberry

One of the most important model species has been tomato (*Solanum lycopersicum*). Aazami et al. (2021) found that iron and zinc oxide NPs enhanced physiology, antioxidant mechanism and expression of genes in tomato in vitro under salt stress conditions (Aazami et al., 2021). EL-Messeiry et al. (2026) showed that *Mentha spicata* extract synthesized CuNPs significantly enhanced the tomato salinity tolerance via physiological and gene-expression changes (EL-Messeiry et al., 2026). El-Tanbouly et al. (2025) observed that CuO NPs derived from *Moringa oleifera* induced higher levels of osmolyte and chlorophyll content under drought stress, and the higher levels of osmolyte were similar to the effects induced by salinity stress. In tomato plants, El-Tanbouly et al. (2025) observed higher levels of osmolyte and chlorophyll content under drought, while the higher contents of osmolytes were comparable to those observed under salinity stress and suggested that the effects induced by CuO NPs derived from *Moringa oleifera* can be applied on a translational basis to salinity stress. Alam et al. (2022) reported in detail the mechanism of action on carbohydrate metabolism, photosynthesis and ROS homeostasis in tomato upon application of Si NPs in salt stressed conditions (Alam et al., 2022). Selim et al., (2025) reported that the synthesized nanoparticles of bimetallic (ZnO/MgO) using plant extract results in a biostimulant effect in cucumber and other cucurbits under seawater stress (Selim et al., 2025). Taqdees et al. (2022) demonstrated that Si and Zn NP biochar enhanced germination, antioxidant defence and nutrient status in radish under NaCl (Taqdees et al., 2022). Phytofabricated gold NPs regulated salt stress responses, redox homeostasis and physiological adaptations in spinach (Amir et al., 2024). GO NPs improved the photosynthetic efficiency and gas exchange in strawberry under salt and alkalinity stress, and served as a comparative benchmark for carbon nanomaterials, MO-NPs (Malekzadeh et al., 2023).

4.4 Other Crops and Synergistic Interventions

In addition to cereals, legumes and common vegetables, phyto-fabricated MO-NPs have been assessed in Lemongrass

(Mukarram et al., 2023), Cotton (Liang et al., 2023), *Citrus sinensis* (Saeedi et al., 2024), *Portulaca* (Movahedi et al., 2025), and Sesame (Rashidpour et al., 2025). The performance of the photosynthetic apparatus was enhanced by the use of chitosan-selenium nanocomposites in salt-stressed *Citrus sinensis*, which is of significant importance in salt-stressed perennial horticulture (Saeedi et al., 2024). Movahedi et al. observed that MgO and MnO NPs affected biochemical features in moderately halotolerant plant *Portulaca oleracea*, and suggested that extracts of halophytes could offer the potential for special properties in nanoparticle design, which is a little explored field (Movahedi et al., 2025).

The synergistic effect of phytofabricated MO-NPs, AMF and PGPR is particularly interesting. Recently, Khan et al. (2026) systematically showed the synergistic effect of green ZnO NPs and walnut biochar on maize under saline soil (Khan et al., 2026). Taqdees et al. (2022) found that Si/Zn NP-enriched miscanthus biochar had positive impact on the performance of the plant, radish, under NaCl (Taqdees et al., 2022). Ali et al. (2026) discussed engineered biochar nanocomposites, which combine nanotechnology with carbon-based materials, to boost plant resistance to biotic and abiotic stressors (Ali et al., 2026). Alharbi et al. (2023) and Ahmadi-Nouraldinvand et al. (2024) demonstrated that MO-NPs in combination with PGPR and AMF improves salinity mitigation, in comparison to their single use (Alharbi et al., 2023; Ahmadi-Nouraldinvand et al., 2024). The use of CaO NPs along with the production of a nano-biochar improved the drought resistance ability of rice, which can be directly applied to salinity (Bilge et al., 2026). Fouladi et al. (2026) also showed that when nano-Si was combined with silicate solubilizing bacteria and earthworms, it was effective in wheat under salinity (Fouladi et al., 2026). Therefore, the combination of phytofabricated nanomaterials with traditional biological inputs is likely the most agronomically feasible application route.

Table 2: Comparative yield and growth responses of major crops to phytofabricated MO-NPs under salinity stress

Crop	NP type	Optimal dose	Salinity level	Yield/biomass improvement	Application	Reference
Wheat	ZnO	50–100 mg L^{-1}	NaCl irrigation	+18–35 % grain yield	Foliar/seed	Adil et al. (2022); Alharbi et al. (2023)
Wheat	Fe_3O_4	50–100 mg L^{-1}	NaCl	Restored chlorophyll, photosynthesis	Foliar	Kreslavski et al. (2023)
Wheat (saline-sodic)	ZnO + amendments	combined	sodic-saline	Improved yield + soil properties	Soil + foliar	El-Sharkawy et al. (2022)
Rice	Se + ZnO NPs (green)	Foliar	NaCl	+25 % yield-related traits	Foliar	Mishra et al. (2025)
Maize	ZnO (*Sargassum*)	Foliar	NaCl	Improved Na^+/K^+, growth	Foliar	Ashraf et al. (2025)
Maize	ZnO + walnut biochar	Combined	NaCl	Synergistic improvement	Soil	Khan et al. (2026)
Maize	CeO_2	Foliar	NaCl	+21 % yield	Foliar	Liu et al. (2022)
Soybean	TiO_2 (green)	Foliar	NaCl	Restored ion balance	Foliar	Abdelhameed et al. (2025b)
Soybean	MgO	Foliar/soil	NaCl	Improved nutrients	Soil + foliar	Akter et al. (2025); Abou-Zaid et al. (2025)
Vicia faba	ZnO (*Mentha*)	50–100 mg L^{-1}	NaCl	Restored chlorophyll, growth	Foliar	Mogazy & Hanafy (2022)
Barley	Cu (*S. argel*)	25–50 mg L^{-1}	NaCl	Improved growth	Foliar	Shaikhaldein et al. (2024)
Tomato	CuNPs (*Mentha*)	Foliar	NaCl	Improved gene expression, growth	Foliar	EL-Messeiry et al. (2026)
Tomato	Fe + ZnO NPs	Foliar	NaCl	Modulated antioxidants	In vitro	Aazami et al. (2021)
Lemongrass	SiNPs	Foliar	NaCl	Restored photosynthesis + essential oils	Foliar	Mukarram et al. (2023)
Cotton	SiNPs	Foliar	NaCl+low T	Restored photosynthesis	Foliar	Liang et al. (2023)
Radish	Si/Zn-biochar	Combined	NaCl	Improved germination	Soil	Taqdees et al. (2022)
Citrus sinensis	Chitosan-Se	Foliar	NaCl	Restored photosynthetic apparatus	Foliar	Saeedi et al. (2024)
Pea	Zn NPs + proline	Foliar	seawater dilution	Improved yield	Foliar	El-Beltagi et al. (2024)
Spinach	Phytofabricated AuNPs	Foliar	NaCl	Improved redox homeostasis	Foliar	Amir et al. (2024)
Sesame	MgO + AMF	Combined	water stress	Improved metabolites	Soil	Rashidpour et al. (2025)

5. Translational Challenges, Toxicity, and Environmental Considerations

5.1 Phytotoxicity and Dose-Response Considerations

The biostimulatory properties of MO-NPs are the same as the potential for phytotoxicity. In a pioneering but highly impactful synthesis, Yang et al. (2017) reported both beneficial and harmful effects of NP–plant interactions, and effects were particularly influenced by the composition of the particles, dose, route of exposure, and developmental stage of the plant (Yang et al., 2017). Even the relatively benign carbon nanoparticles have been found to cause phytotoxicity at high doses (Parthasarathi, 2011). ZnO NPs at supra-optimal concentrations inhibit root growth, induce leaf chlorosis and oxidative damage, but paradoxically through the same release of Zn ions which are essential for nutrient supplementation (Tripathi et al., 2017). It was observed that NO can mitigate the phytotoxicity of ZnO NPs in wheat by enhancing ascorbate–glutathione cycle, further suggesting that the same redox mechanisms that are protective under salinity stress also seem to be recruited under excess NP induced stress (Tripathi et al., 2017). Jalali et al. (2026) showed that the hydroxyapatite NPs were phytotoxic and genotoxic to *Vicia* *faba* seedlings in a dose-dependent manner, thus, the establishment of safe application limits prior to agronomic use with these NPs is recommended (Jalali et al., 2026).

The hormetic dose-response curve is a recurring concept in the recent literature. Most of the phytofabricated MO-NPs show beneficial effects at low and moderate doses, whereas inhibition and toxicity are observed at high doses (Mogazy & Hanafy, 2022; Adil et al., 2022; Mishra et al., 2025). The beneficial window is significantly different for various materials, for example, ZnO and Fe systems exhibit wide windows, while CuO and some TiO_2 phases have narrower windows limited by metal-ion toxicity (Shaikhaldein et al., 2024; EL-Messeiry et al., 2026). Soils, crops and growing stages are therefore the fundamental prerequisites for safe deployment and establishing the optima for each.

5.2 Effects on Soil Microbiome and Rhizosphere Ecology

The soil microbiome, a community of bacteria, archaea, fungi, protists, and viruses, which underpin soil structure, plant–microbe interactions, and nutrient cycling, is increasingly recognised as an important driver of salinity tolerance. The interaction of MO-NPs with this community is being mapped. The authors of Wang et al. (2023) reviewed the interaction between metal-based NPs and the plant rhizosphere micro-environments, highlighting that the nano-properties that make metal-based NPs effective in plants, such as surface reactivity, ion release and charge-driven adsorption, can also alter the microbial diversity of the rhizosphere. In an Ag NP microcosm system, Wu et al. (2021) followed dissolution processes and the accumulation of Ag NPs at the soil–plant–microbe interface and found that the microbiota surrounding the Ag NP can significantly influence its fate (Wu et al., 2021). An above-ground application of CeO_2 nanomaterials was shown to change the rhizobacterial community of salinity stressed maize, a long range effect which was attributed to altered root exudation (Liu et al., 2022). The impacts of wider effects on AMF colonization were variable: TiO_2 NPs gave an extra advantage to symbiotic colonization by *F. mosseae* in El-Gazzar et al. (2020), whereas SiO_2 NPs resulted in an additional benefit when inoculated with AMF and rhizobacteria in Ahmadi-Nouraldinvand et al. (2024). But dose-dependent suppression of the microbial functional groups has also been reported at higher concentrations.

There are still several important knowledge gaps: (i) persistence of MO-NPs in agricultural soils after repeated use; (ii) transformation of pristine NPs to sulphidized, oxidized and organic-coated forms affecting bioavailability; (iii) effects of NP use on key microbial taxa such as nitrifiers, denitrifiers, and N-fixers; and (iv) propagation of NP-induced shifts through trophozoonic levels in agroecosystems (Wang et al., 2023; Chittibomma et al., 2023).

5.3 Environmental Fate, Transformation, and Food-Chain Considerations

The environmental fate of phytofabricated MO-NPs has barely been characterised. In chemically synthesized systems, dissolution, surface chemistry transformation, aggregation and bioavailability are complex processes to describe the long-term behaviour of NPs in soils. The organic corona in phytofabricated systems further adds to the complexity of fate prediction due to the plant/batch-specific nature of the composition. In this regard, Wang et al. (2023) and Wu et al. (2021) note explicitly the need for consideration of soil-mediated transformations of NPs in nanosafety assessments (Wang et al., 2023; Wu et al., 2021). Food-chain considerations are especially relevant as application of NP may result in the accumulation of Zn, Fe, Cu, Ti, Mn, or Ce in edible parts of crops and lead to potential dietary exposure. Mazhar et al. (2023) wrote about the wheat and rice grain Zn fortification with ZnO – NPs, which is a good biofortification effect, but other elements present in the grain (e.g., Cu, Ti) could, in principle, be present at higher levels in the grain as a result of the same pathway of accumulation. In this regard, robust data on both dose–response and residue and migration along the soil–plant–consumer continuum are immediate needs.

5.4 Regulatory, Scalability, and Economic Barriers

The global regulatory environment for agricultural nanomaterials is still evolving. There is no global harmonisation of the regulatory definition for nano-biostimulant and different jurisdictions classify it differently such as under the fertilizer, biostimulant, plant-protection or general-chemical regulations (Chittibomma et al., 2023; Ajanaku et al., 2025). The lack of standardized minimum characterization requirements (size distribution, crystallinity, impurity profile, corona composition) further complicates pre-market evaluation. The extra complexity in the case of phytofabricated NPs is that the active substance is not a single chemical, but a hybrid of the inorganic core and the organic shell (plant) and can vary batch to batch.

Scalability is a huge obstacle. Most known phytofabrication protocols produce less than a gram of phytofabrication in lab environment and have wide inter-batch variability, depending on the composition of the extracts used. To prepare extracts at the multi-kilogram or multi-tonne level, a standardised preparation method for extracts (possibly using defined plant biomass with quality controlled phytochemical profile) is needed, as well as continuous-flow synthesis reactors and post synthesis purification steps to ensure the bioactive corona is not lost whilst removing any residual organics. Additionally, the choice of plant biomass is crucial for the economic feasibility of phytofabrication of MO-NPs, with waste streams like rice husk (SiO_2) or Moringa leaf residues (CuO) being promising sources depending on the plant and availability (El-Tanbouly et al., 2025; Gonc et al., 2024), while alternative uses, such as food, feed, or biofuel production, should be taken into account.

5.5 Critical Comparison: Phytofabricated versus Chemically Synthesized NPs

One of the most important yet under-discussed questions is whether the phytofabricated MO-NPs are really more effective at salinity mitigation than the chemically-synthesized MO-NPs, or whether the difference is environmental. In maize, green-synthesized NPs have been shown to be as effective or superior to those derived via chemical routes, with added biocompatibility (Ashraf et al., 2025); In Vicia faba, green-synthesized NPs were as effective

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or more effective than their chemical-route counterparts, with enhanced biocompatibility (Mogazy & Hanafy, 2022); In soybean, green-synthesized NPs have been found to be as effective or superior to their chemical-route counterparts, showing better biocompatibility (Abdelhameed et al., 2025a; Abdelhameed et al., 2025b). Mechanistic explanation typically points to the phytochemical corona as an additional source of antioxidant, signalling and biocompatibility benefits. Notably, few studies directly compare phytofabricated and chemically synthesized NPs in comparable conditions; most comparisons are done implicitly across studies, the methodological approach is weak. It is recommended that future studies include explicit head-to-head comparisons and include other controls, such as corona characterization (e.g., liquid-chromatography–mass spectrometry) and corona-stripping (e.g., repeated washing or chemical removal of the organic layer) to isolate the contribution of plant-derived components.

5.6 Knowledge Gaps and Inconsistencies

In the corpus examined here, some common discrepancies can be observed. First, the same NP type and dose may elicit opposite responses in different crops or even cultivars; for instance, Aazami et al. (2021) found that the effects of Fe/Zn oxide NPs varied depending on the cultivar in tomato (Aazami et al., 2021). Second, the correlation between salt tolerance and the NP-induced changes in proline is sometimes positive and sometimes negative when proline is used as an osmolyte or stress marker, respectively (Alharbi et al., 2023; El-Beltagi et al., 2024). Third, results from hydroponic or pot experiments may not be applicable to field experiments due to variability in irrigation water and soil mediated NP transformation and microbial buffering. Fourth, there is no uniformity in the quality of "green" synthesis: the parameters used in the extract preparation (boiling water or cold maceration) and the parameters used for calcination (calcination temperature) and characterization (rigor) are not uniform from study to study, and quantitative comparisons between studies are therefore dangerous. Fifth, it is frequently not possible to isolate the effect of the co-applied biostimulants, biochar or microorganisms from the total effect, which may be results in overestimation of the NP-specific effect.

6. Future Perspectives and Conclusions

The metal-oxide nanoparticles produced using plants are in a translational limbo. Based on the accumulated mechanistic evidence, they can be conceptually termed as nano-biostimulants for salinity stress mitigation (Singh et al., 2025; Anand & Arora, 2026; Ashraf et al., 2025; Abdelhameed et al., 2025a; Abdelhameed et al., 2025b; Wu et al., 2025). Simultaneously, methodological disintegration, dose-response variability and inadequate environmental and regulatory characterization represent the main impediments for deploying the field. We describe five directions for future research.

First one is the multi-omics integration. The systems level's resolution with transcriptomics, proteomics, metabolomics and ionomics in phytofabricated MO-NP experiments will enable distinguishing the direct effects of NPS from the cascades of indirect effects. Specific gene families associated with salinity stress tolerance, like SOS, NHX, HKT, antioxidant enzymes, AsA-GSH cycle enzymes, ABA and JA biosynthesis should be included in these studies and correlated with corona composition data (Gholizadeh et al., 2025; Anand & Arora, 2026). Only a handful of multi-omics studies of NP–plant–salinity interactions have been reported and indicate that it is more network-based than the linear models typically presented in the review schemes.
Secondly, are the field validation and standardization. There is a strong bias in the existing evidence base towards pot and hydroponic experiments. To validate the results, field-scale trials in realistic irrigation regimes and realistic economic endpoints, replicated in different saline agro-ecological zones, have become a necessity (Adil et al., 2022; Alharbi et al., 2023; Khan et al., 2026). To document particle synthesis, characterization, dose and exposure, salinity level and phenotypic outcomes, a standardisation of reporting protocols should be established, similar to MIRO or CONSORT in other fields.

Third is the intelligent delivery systems. Understanding the stimuli needed to trigger the release of MO-NPs from the controlled-release platform (stimulus-responsive coatings, hydrogels, biochar carriers, encapsulated foliar sprays) presents a potential pathway for optimizing efficacy at a minimum dose and exposure. Engineered biochar nanocomposites (Ali et al., 2026; Khan et al., 2026; Taqdees et al., 2022; Bilge et al., 2026) and NO-releasing nano-formulations (Oliveira et al., 2016; Seabra et al., 2022) represent two promising design philosophies. Targeting of NPs to the rhizosphere or stomatal aperture by smart delivery may also minimize environmental spread of NPs.

Fourth, AI-optimized synthesis and screening. Machine-learning tools which connect plant-extract phytochemical fingerprints, synthesis conditions, particle characteristics, and the resulting phenotype can expedite the identification of the best phytofabrication strategies. Due to the multidimensionality of the corona–crystal–phenotype space, a traditional approach of one variable at a time experimentation is not expected to be efficient. The same methods can be used to assist regulatory decision making by predicting toxicity and environmental fate from the synthesis side of the equation.

Fifth one is the corona engineering by using the halophytes. The potential of nanoparticles capped with phytochemicals derived from halophytes that could be "pre-adapted" for salinity environments is an exciting concept that has not been explored yet systematically, and thus merits experimental testing (Atzori et al., 2025; Székely & Barta, 2025; Salem et al., 2025). Comparative studies of NPs synthesized from mesophyte and halophyte extracts, prepared using the same conditions, might reveal measurable advantages of the corona biology of stress-adapted plants.

The adoption of the potential of phytofabricated MO-NPs will need to be supported by a unified regulatory framework that considers the hybrid inorganic–organic nature of these materials, promotes transparent characterization, establishes residue limits in edible tissues and encourages LCA. The recent FAO discussion on nano-enabled agriculture, as well as national discussions in India, China and the EU, show that policy is starting to "catch up" with the science, and strict and transparent review processes like this can assist in these policy development exercises.

Finally, it can be concluded that the phyto-fabricated metal-oxide nanoparticles are an interesting, agronomically promising and environmentally aspirational class of nano-biostimulants for salinity stress mitigation. The evidence gathered over the years in cereals, legumes, vegetables and oilseeds and the fact that mechanistic understanding from antioxidant biology, ion-transport physiology, photosynthesis, hormone signalling and nanozyme catalysis has all converged, points to a cautious optimism. But the field needs to be developed in a methodological way: standardization of synthesis and characterization, testing of the efficiency in the real field, characterization of the ecotoxicological aspect and the regulatory aspect, and explicit test of the added value phytochemical corona. Such maturation could make phytofabricated MO-NPs a part of the larger climate-smart, sustainable-agriculture toolbox available to the world's growing population of salt-affected lands.

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