

INTEGRATING NANOTECHNOLOGY AND BIOSTIMULANTS INTO BIO-SALINE FARMING: AN OVERVIEW

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Abstract

Bio-saline farming is a promising approach to face the global soil salinization and degradation. It is one of the most practical solutions available for climate adaptation and food security, especially in arid and coastal regions. Among the sustainable solutions in bio-saline systems, the integration of bio stimulants and nanotechnology represents a promising strategy for sustainable bio-saline agriculture. Nanotechnology and biostimulants are increasingly integrated to enhance the sustainability and productivity of bio-saline farming, where crops must withstand high salt levels. Nano-formulations can improve the stability, efficiency, and targeted delivery of biostimulants, allowing plants to better regulate ion balance, strengthen antioxidant defenses, and maintain physiological activity under salinity. Nano-formulations of micronutrients, chitosan, or plant-derived bioactives can penetrate plant tissues more effectively, depending on nanoparticle characteristics, plant species, application method, and environmental conditions, enabling controlled release and prolonged action. When combined with bio stimulants, they help enhance potassium retention, reduce sodium uptake, and promote osmotic adjustment, depending on dose, material, and crop. This integration also boosts photosynthesis, nutrient acquisition, and root development, making crops more resilient to salt-induced oxidative stress. As a result, Nano-formulations of bio stimulants offer a promising approach to improving crop production and supporting sustainable agriculture in salt-affected soils. Despite these advantages, sustainable application of Nano-formulations in saline agriculture requires a comprehensive assessment of their toxicity, environmental fate, bioaccumulation potential, and long-term effects on ecosystem health. Further studies are needed concerning the Nano toxicity of such Nano-formulations of bio stimulants.

Key words: Amino acids; Halophytes; Humic substances; Plant extracts; Trichoderma

Introduction

Soil salinization represents a critical global threat that severely impairs crop production and agricultural sustainability. Globally, rising soil salinity has emerged as one of the most pressing challenges facing modern agriculture, driven by climate change, poor drainage, and unsustainable irrigation practices (Wang N *et al.*, 2026). Alongside with climate change, the situation is worsening due to the harmful impacts of these changes accelerating the soil salinization in several regions all over the world (Mukhopadhyay *et al.*, 2021). Soil salinity represents the chemical state of high soluble salt concentrations in the soil solution causing plant physiological drought, whereas salinization is the dynamic process of salt accumulation over time due to high evaporation or saline irrigation; in contrast, sodification refers specifically to the accumulation of exchangeable sodium ions on the soil complex, which degrades soil physical structure, seals pores, and restricts water and air infiltration (Sentís & Arora, 2025).

More than 1000 million ha of cultivated lands and their productivity are posted to soil salinization, leading to a reduction in global food production around 50% in the 21st century, as well as annual global loss in agricultural production of about US\$ 1.27–2.73 billion. Cultivated soils

affected by soluble salts are spreading in 100 countries and regions, such as Africa, China, Egypt, Pakistan, India, Iran, Australia, and the United States (Wang N *et al.*, 2026). It is reported by FAO that approximately 20% of irrigated croplands are considered salt-affected soils (Lei *et al.*, 2025). Globally, around 1.38 billion hectares of salt-affected soils severely restrict agricultural potential (Qiao *et al.*, 2026). Soil salinization mainly cause a reducing in vegetation water uptake, impeding soil respiration, disrupt nitrogen cycling, and decrease organic matter content, whereas soil sodification lowers soil infiltration rate and increases vulnerability to wind and water erosion (Wang T *et al.*, 2025). For overcome soil salinization, the concept of bio-saline farming was addressed describing agriculture using wide levels of salinity in soil or groundwater or both (Gheyi *et al.*, 2023).

The bio-saline approach aligns with the concept of saline agriculture, which emphasizes using halophytes, aliphilic plant growth promoting microorganisms and other bio-formulations to mitigate salinity stress (Choukr-Allah and Ragab 2023; Vineeth *et al.*, 2023). On the other hand, several common strategies of mitigation for tackling soil salinity such as cultivation of tolerant genotypes (Cui Y *et al.*, 2025), applied organic amendments (Liu B *et al.*, 2025), suitable fertilization and irrigation (Xia H *et al.*,

2025), drainage and land use strategies (Heng *et al.*, 2022), phytoremediation (Naz *et al.*, 2023), and bioremediation techniques have successfully tackled the soil salinity issue (Ezenwanne *et al.*, 2026). Nowadays, the industry of agriculture is undergoing a major transformation by applying emerging technologies in different field such as for efficient water use in agriculture (Antu *et al.*, 2024), agricultural wastes for circular bio-economy (Nassary 2025; Ayele *et al.*, 2026), and emerging nanotechnology for sustainable agriculture (Nguyen *et al.*, 2024). Biostimulants recently were linked with nanotechnology for crop health management (Noman *et al.*, 2024), for early-stage plant development (Sánchez-Campos *et al.*, 2026), and for enhancing plant resilience under abiotic stress (Shaheen *et al.*, 2026). In bio-saline farming, very few publications on the applied nano-biostimulants could be noticed (Agrawal *et al.*, 2025).

Therefore, this review focuses on (1) how combining nanotechnology with biostimulants alters plant biochemical, physiological, and molecular responses to mitigate salt stress, (2) how nano-encapsulated biostimulants improve the targeted, slow-release delivery of active ingredients compared to traditional biostimulants, minimizing leaching and degradation in saline environments, (3) how nano-biostimulants impact the soil microbiome, nutrient availability, and physical structure of saline soils, and (4) to highlight the primary limitations preventing large-scale field adoption, including high synthesis costs, field stability issues, and potential environmental toxicity.

Ecophysiology of salt stress in plants: Salinity is one of the major environmental stresses that significantly impacts the growth and productivity of higher plants. The causes of this stress are numerous, including the use of highly saline wastewater for irrigation and soil salinization, which is also a major source of this stress (Aycan, 2026). A comprehensive understanding of how the higher plants respond to salinity stress is essential for improving their tolerance to salt stress. Salinity negatively affects higher plants through its adverse effects on photosynthesis and the absorption of water and nutrients (Badavath & Saski, 2026). The concentration and type of proteins, amino acids, sugars, and carbohydrates are also negatively affected by salinity. Generally, salinity stress causes changes in the metabolic and physiological processes of higher plants, depending on the intensity and duration of the stress (Fathi *et al.*, 2026). The ecophysiological impacts of salinity stress on plants could be linked with both biostimulants and nanomaterials. Furthermore, both biostimulants and nanomaterials target the same ecophysiological bottlenecks created by salinity stress which involve oxidative stress, osmotic imbalance, ion toxicity, and disruption of photosynthesis. They do so through different but partly overlapping mechanisms, often converging on improved ion homeostasis, ROS detoxification, photosynthetic function, and molecular signaling (Table 1).

Different applied nano-based materials (i.e., NPs, NMs, nanofertilizers, nano-enabled carriers) can impact plant ecophysiology under salinity by scavenging of reactive oxygen species (ROS) and antioxidant activation (mainly CAT, APX, and SOD), ion homeostasis regulation, photosynthesis protection (as ZnO and Si-NPs can sustain PSII efficiency and increase chlorophyll content under salinity), improved water relations and

osmotic balance (like Nano-Si enhances aquaporin function and osmotic adjustment), and modulation of salinity stress signaling and plant hormones (Abideen *et al.*, 2022; Alhammad *et al.*, 2023; Singh *et al.*, 2023; Khan *et al.*, 2025; Gholizadeh *et al.*, 2026). Therefore, nanomaterials directly buffer plants against the physiological and molecular drivers of salinity-induced decline, leading to improved growth, water use efficiency, and yield under salt stress. The same behavior of biostimulants (e.g., amino acids, humic/fulvic acids, seaweed extracts, protein hydrolysates, and microbial inoculants) can be noticed by re-balance physiological processes disrupted by salinity, restoring photosynthesis, nutrient uptake, oxidative stability, and growth.

Oxidative and osmotic stress: When higher plants are exposed to salinity, they actually experience two types of stress. The first is osmotic stress, which is the first response of higher plants (Aufar & Azwar 2026). Increased salinity in the root zone leads to a decrease in soil water potential, and consequently, a decrease in the plants' ability to absorb water. This results in symptoms similar to water deficit stress, such as decreased cell turgor pressure and impaired cell elongation, leading to stunted root and shoot growth. All of this negatively affects transpiration and photosynthesis. The other type of stress caused by salinity is called oxidative stress (Llanes, 2026). This stress causes an increase in the production of reactive oxygen species (ROS) in plant tissues, such as H_2O_2 and O_2^- . When these compounds accumulate in large quantities within plant tissues, they damage biofilms and oxidize both nucleic acids and proteins (Nigam *et al.*, 2026). All of this negatively affects photosynthesis, plant growth, and crop yield. Figure 1 displays the oxidative and osmotic stress on plants.

Ion toxicity and nutrient imbalances: One of the most significant harmful effects of salt stress is the accumulation of both chloride and sodium ions within the tissues of higher plants growing under saline conditions (Altaf *et al.*, 2025). The influx of these ions into the tissues causes a severe imbalance in ions, resulting in serious physiological disturbances and the disruption of the activity of many vital enzymes. For example, high sodium concentrations within plant cells inhibit potassium absorption, a crucial element for higher plants and essential for growth and productivity (Derbew *et al.*, 2026). Sodium accumulation also limits the absorption of both calcium and magnesium. This nutrient imbalance negatively impacts vital processes such as protein synthesis, signal transduction, and stomatal opening and closing, thus affecting plant growth, photosynthesis, leaf area, and other characteristics indicative of plant performance (Maitra *et al.*, 2026). Table 2 illustrates the reported effects of salinity on higher plants, while Fig. 2 displays the ion toxicity and nutrient imbalances and associated consequences on plants.

Generally, it can be said that the osmotic stress generally represents an early response to salinity, whereas ionic and oxidative stresses can develop or intensify subsequently, with substantial overlap among these stress responses. Additionally, It can be said that the accumulation of toxic ions such as Na^+ and Cl^- impairs K^+ uptake and disrupts vital plant processes like photosynthesis, triggering essential molecular defense strategies. Plants counter this by employing the SOS1 system to extrude excess sodium, while

vacuolar NHX transporters sequester ions to prevent toxicity and maintain osmotic balance. Together with high-affinity transporters like HKT and HAK that restore ionic equilibrium and lower the Na⁺/K⁺ ratio, these mechanisms safeguard plant tissue and sustain growth under saline conditions (Aufar & Azwar, 2026; Derbew *et al.*, 2026; Maitra *et al.*, 2026; Nigam *et al.*, 2026).

Conventional biostimulants in Bio-Saline farming:

Conventional non-microbial and microbial biostimulants, including amino acids, humic and fulvic acids, seaweed extracts, protein hydrolysates, organic amendments, plant growth-promoting rhizobacteria (PGPR), compost, biofertilizers, and chitosan-based products, play a central role in bio-saline farming by directly counteracting ecophysiological constraints such as oxidative stress, osmotic stress, ionic imbalance, nutrient unavailability, and impaired photosynthesis. While these bio-based substances

(categorized in Table 3 and Fig. 3) consistently demonstrate an ability to enhance plant tolerance, growth performance, and biological processes under saline stress, their practical application remains constrained by fundamental physiological and physicochemical bottlenecks. Conventional formulations frequently suffer from rapid environmental degradation, extensive soil leaching, poor thermal and chemical stability, low leaf-cuticle permeability, and inefficient delivery to target plant tissues. These operational limitations severely reduce bio-availability and field efficacy under harsh saline conditions, thereby establishing the direct scientific rationale for integrating nanotechnology. By encapsulating or loading conventional biostimulants onto nano-carriers, nano-enabled biostimulants offer targeted delivery, controlled release, enhanced membrane permeability, and protection against degradation, representing the next evolutionary step for sustainable crop production in salt-affected agroecosystems.

Table 1. The link between ecophysiological attributes with both nanomaterials and biostimulants.

Ecophysiological target	Suggested nanotechnology mechanisms	Suggested biostimulant mechanisms	References
ROS / Oxidative stress	Nanozymes, antioxidant enzyme activation	Antioxidants, enhanced enzyme activity	Zia-ur-Rehman <i>et al.</i> , (2023); Gholizadeh <i>et al.</i> , (2026) Ikuyinminu <i>et al.</i> , (2023);
Ion homeostasis	SOS1/NHX1/HKT regulation	Improved K ⁺ /Na ⁺ transport	Coêlho <i>et al.</i> , (2025); Abideen <i>et al.</i> , (2022)
Photosynthesis	PSII protection, chlorophyll stability	Chlorophyll enhancement, PSII efficiency	Siddiqui ZS <i>et al.</i> , (2025); Silva <i>et al.</i> , (2025)
Osmotic adjustment	Osmolyte induction	Proline and sugar accumulation	Singh <i>et al.</i> , (2024); Di Mola <i>et al.</i> , (2024)
Stress signaling	Hormonal and gene regulation	Transcriptome-level reprogramming	Khan <i>et al.</i> , (2025); Cha <i>et al.</i> , (2021)

Abbreviations: ROS= Reactive oxygen species; SOS1= Salt overly sensitive 1; NHX1= Na⁺/H⁺ Antiporter family; HKT= High-affinity potassium transporter

Table 2. Reported effects of salinity on higher plants.

Plant species	Salinity conditions	Observed negative effects	References
Strawberry (<i>Fragaria × ananassa</i>)	Salt stress (0, 50, and 100 mM NaCl)	Salinity decreased total dry weight, total soluble protein, while increased H ₂ O ₂ , malondialdehyde and proline; SOD and POD enzymes activity	Dedejani <i>et al.</i> , (2021)
Broccoli (<i>Brassica oleracea</i> L.)	Saline soil and irrigation water (EC: 7.3 and 4.2 dSm ⁻¹ , respectively)	High salinity stress led to a significant reduction in the growth and yield of broccoli, but applied humic acid mitigated this stress	Al-Falahi <i>et al.</i> , (2022)
Peanut (<i>Arachis hypogea</i> L.)	Plants irrigated with saline water (50 mM NaCl)	Salinity led to an increase in the uptake of Na ⁺ and resulting in an increase in the value of MDA	Alves <i>et al.</i> , (2022)
Potato (<i>Solanum tuberosum</i> L.)	Salt-affected soil (EC 7.14 dSm ⁻¹)	Soil salinity negatively affected plant height, fresh and dry weight, leaves area, chlorophyll a and b and carotenoids	Selem <i>et al.</i> , (2022)
Cucumber (<i>Cucumis sativus</i> L.)	Salt stress levels (50, 100 mM NaCl)	Increasing salinity led to reduce the fruit yield and quality, but mitigated by application of Se and grafting using pumpkin rootstock	Amerian <i>et al.</i> , (2024)
Barley (<i>Hordeum vulgare</i> L.)	Soil salinity, EC 7.3 dSm ⁻¹	Salinity of soil caused a reduction in the productivity of two barley varieties	El-Shaboury & Baddour (2024)
Maize (<i>Zea mays</i> L.)	Saline irrigation water levels: 3 and 5 g L ⁻¹	Salinity level significantly impacted water-salt dynamics, ultimately reducing maize grain yield	Zhou <i>et al.</i> , (2024)
Maize (<i>Zea mays</i> L.)	Saline soil, EC at 4.35 dSm ⁻¹	EC value negatively affected maize performance and productivity	Abd EL-Azeiz <i>et al.</i> , (2025)
Tomato (<i>Solanum lycopersicum</i>)	Saline soil with EC value of 6.25 dSm ⁻¹	Growth criteria, photosynthetic pigments, fruit yield and fruit quality were negatively affected due to high salinity of soil	Ahmed <i>et al.</i> , (2025)
Tomato (<i>Solanum lycopersicum</i>)	Soil having EC value of 8.1 dS m ⁻¹	High salinity stress led to a significant reduction in the morphological and physiological traits of ten tomato varieties.	Bayoumi <i>et al.</i> , (2025)
Mung bean (<i>Vigna radiata</i> L.)	Salinity levels of 3.0, 5.0 mScm ⁻¹	Increased salinity led to reduce the germination, growth criteria and nutrient uptake as well as yield	Adak <i>et al.</i> , (2026)
Wheat (<i>Triticum durum</i> L.)	Saline irrigation levels (0.2, 8, 12, and 16 dSm ⁻¹)	Saline irrigation led to an increase in soil EC and sodium accumulation, resulting in adverse effects on the growth criteria and productivity	Manhou <i>et al.</i> , (2026)
Red cabbage (<i>Brassica oleracea</i>)	Salt stress to plants at 50 mM NaCl	The studied salinity negatively affected red cabbage growth performance	Mingil & Dasgan (2026)
Wheat (<i>Triticum aestivum</i> L.)	Saline-alkali soils	The soil conditions negatively affected biomass, length, and volume of wheat roots	Zhang <i>et al.</i> , (2026)

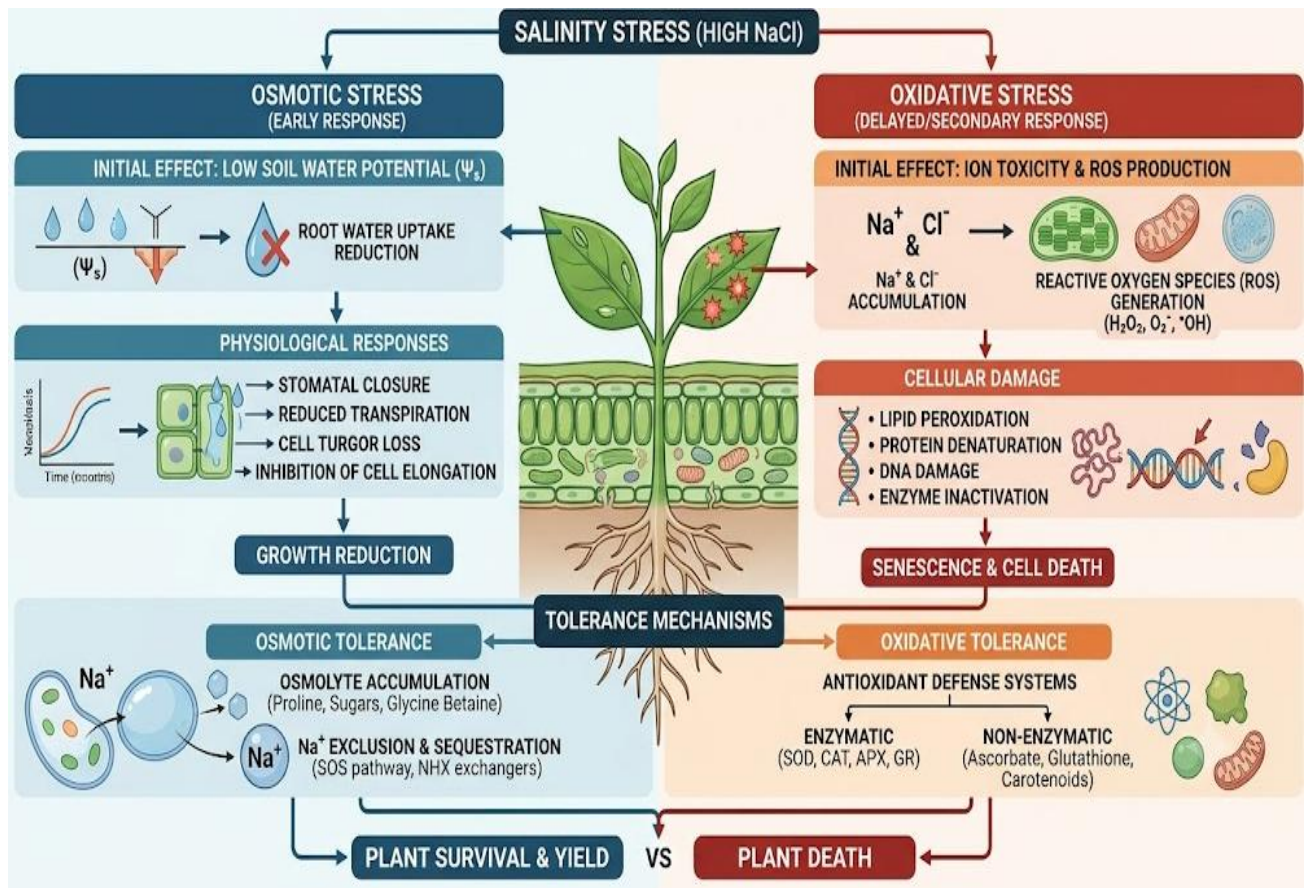


Fig. 1. The suggested impacts of oxidative and osmotic stress on plants under salinity stress.

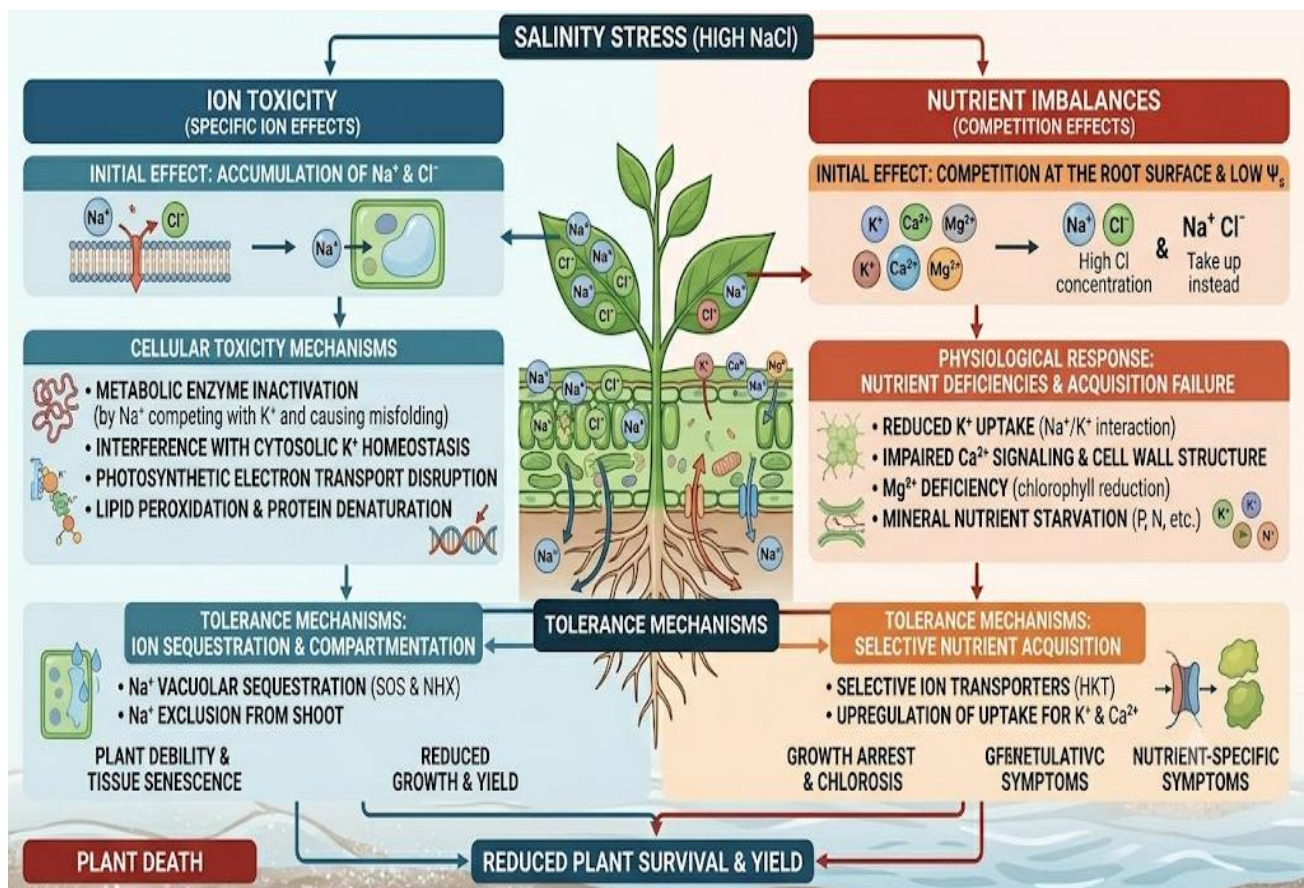


Fig. 2. Impacts of ion toxicity and nutrient imbalances on plants under salinity stress.

Table 3. List of the main biostimulants types and their role in mitigation of saline soils.

Biostimulant type	Key mechanisms in saline soil and normal conditions	References
Humic and fulvic acids	Reduce Na ⁺ accumulation, EC and pH; improve macro-aggregates, porosity, organic matter; enhance nutrient uptake; increase chlorophyll, photosynthesis, water status, and boost antioxidant enzymes	Hernández-Campos <i>et al.</i> , (2023)
Amino acids/ plant-derived extracts	Improve osmotic adjustment, reduce oxidative stress, enhance antioxidant capacity, support salt-adaptive metabolism	Alfosea-Simón <i>et al.</i> , (2020)
Protein hydrolysates	Enhance root and shoot growth, increase osmolytes, restore nitrogen metabolism and photosynthesis, reduce oxidative stress	Starr <i>et al.</i> , (2026)
Chitosan and derivatives	Maintain ionic balance (K ⁺ /Na ⁺), enhance antioxidants, promote root development under stress; boosts nutrients availability and uptake efficiency	Soostani <i>et al.</i> , (2025)
Plant extracts (in general)	Reduce oxidative stress, improve water status, enhance chlorophyll and growth under salinity; increase antioxidant defense by scavenging ROS	Pandey <i>et al.</i> , (2025)
PGPR/Microbial biostimulants	Produce IAA, siderophores, EPS; enhance N/P cycling; improve K ⁺ /Na ⁺ homeostasis; increase antioxidant enzymes; reshape rhizosphere microbiome	Ezenwanne <i>et al.</i> , (2026)
Seaweed extracts	Improve K ⁺ /Na ⁺ balance, increase osmolytes (proline, sugars); Enhance antioxidant enzymes (SOD, POD, CAT), maintain chlorophyll and PSII efficiency, increase yield under salinity	Sahin (2025)
Organic amendments (compost, manure, straw, biochar)	Reduce EC, Na ⁺ , Cl ⁻ ; improve SOC, CEC, porosity; increase NPK availability; promote beneficial microbes; sequester saline-alkali soil organic carbon; reduce CO ₂ & CH ₄ but increase N ₂ O emissions during hot periods	Ma <i>et al.</i> , (2026), Hu <i>et al.</i> , (2026)
Inorganic biostimulants like potassium-based	K can regulate several physiological and metabolic plant processes like stomata closure, photosynthesis, respiration, osmoregulation, support ionic homeostasis and stress mitigation under saline soil conditions	Praveen & Singh (2024)
Biofertilizers (AMF, Trichoderma)	Enhance nutrient uptake, root vigor, photosynthesis, soil enzymes; modulate soil communities	Sarin <i>et al.</i> , (2025)
Microalgae-based extracts	Soil microalgae-based extracts can sustainably improve plant growth and production as linked to bioactive molecules like polyphenols, and indole-3-acetic-acid; mitigate oxidative stress under salinity conditions	Chabibi <i>et al.</i> , (2026), Marka <i>et al.</i> , (2026)
Tannin-based extracts	Strengthen root architecture, increase root length and weight; Improve salinity tolerance	Makhubalo <i>et al.</i> , (2024)
Mixed formulations	Synergistically improve crop yields and competitiveness under saline-related stress	Wahid <i>et al.</i> , (2026)

PGPR= Plant growth regulators Rhizobia

Table 4. Nano-enabled vs. conventional biostimulants in bio-saline farming.

Comparison item	Nano-enabled biostimulants	Conventional approaches	Main difference	References
Delivery and persistence	Designed for targeted delivery, improved bioavailability, controlled release, and better shelf life through nanocarriers	Often rely on plant extracts, protein hydrolysates, microbial inoculants, seaweed products, or mineral foliar inputs, which can be more vulnerable to degradation or loss	Nano-enabled systems are the more precision-oriented platform	Edussuriya <i>et al.</i> , (2026); Sow <i>et al.</i> , (2026); Magnabosco <i>et al.</i> , (2023)
Consistency across conditions	Expected to be more consistent because of engineered delivery, but real-world performance remains uncertain	Effects can vary with soil type, dose, crop genotype, and timing	Conventional approaches are effective but more variable	Durgude <i>et al.</i> , (2026); Magnabosco <i>et al.</i> , (2026)
Salinity mitigation performance	Promising for stronger and more durable stress alleviation, but still needs more field validation	Already shown to improve root growth, antioxidant defense, ion balance, photosynthesis, and yield under salinity in multiple crops	Conventional products are proven and practical now, as nano-enabled ones are more advanced but less validated at scale	Agrawal <i>et al.</i> , (2025); Mehmood <i>et al.</i> , (2024)
Soil health effects	Potential to reduce losses and improve delivery, but long-term soil impacts are still a concern	Can improve soil structure, cation exchange capacity, aggregate stability, and beneficial soil biology	Conventional biostimulants have clearer evidence for soil-health benefits	Imran <i>et al.</i> , (2026); Roche <i>et al.</i> , (2024)
Risks and limitations	Main concerns are cost, regulatory uncertainty, and possible human or environmental safety issues from persistence	Main limitations are variable efficacy and dependence on application context	Nano-enabled approaches face bigger governance and safety hurdles	Khalid <i>et al.</i> , (2025); Upadhyay <i>et al.</i> , (2025)

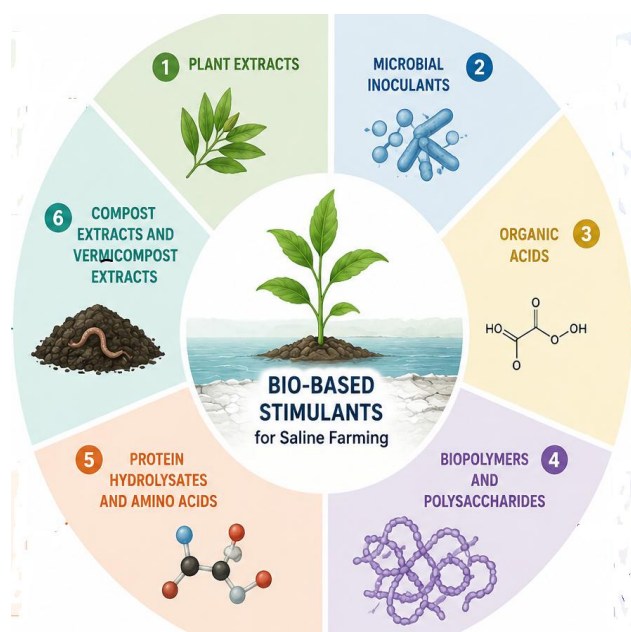


Fig. 3. Some categories of bio-based stimulants used in saline farming.

(1) Humic substances: the main active components of this group are humic compounds, and organic acids. They are organic carbon-rich materials enhancing nutrient uptake, root growth, antioxidants, and ion homeostasis under salinity. They mainly include humic and fulvic acids along with humate, and repeatedly classified as major biostimulant groups (Ibraevaa *et al.*, 2026).

(2) Seaweed and algal extracts: seaweed and algal extracts (brown/green seaweed extracts, cyanobacteria extracts, brown/red/green algae and microalgae) are one of the most consistently documented groups used under salinity. The main active compounds of this group involve alginates, betaine, phytohormones, and polysaccharides. They improve Na^+/K^+ ratios, antioxidants, photosynthesis, and metabolic reprogramming. Cyanobacteria and microalgae also function as biostimulants through phytohormones, EPS, and osmoprotectants (Hilles *et al.*, 2026; Ummalyma & Sreelekhmy, 2026).

(3) Protein hydrolysates and amino acid biostimulants: this group includes plant or animal protein hydrolysates, and amino acids. They are key bio-based categories peptide- and amino acid-rich compounds acting on metabolism, osmolytes, antioxidant pathways, and photosynthesis improving osmotic adjustment, nitrogen metabolism, and root and shoot growth under saline conditions (Zamljen *et al.*, 2023; Ahmad *et al.*, 2025).

(4) Plant-derived extracts: extracts rich in phenolics, flavonoids, polyphenols, antioxidants, and vitamins in root/shoot extracts. Plant extracts act through antioxidant and osmoprotective pathways and are strongly supported for salt mitigation by improving osmotic adjustment, and ROS detoxification. Examples may include moringa leaf, garlic extract, citrus extracts, licorice extract, aloe vera extract, and green tea extract (Han *et al.*, 2024; Tripathi *et al.*, 2024; Helene *et al.*, 2026).

(5) Microbial biostimulants: this group has many sub-groups such as arbuscular mycorrhizal fungi (AMF), plant growth promoting rhizobacteria (PGPR) and *Trichoderma* along with endophytes, and beneficial soil microbes. They can enhance nutrient cycling, increase salt tolerance via hormone modulation, nutrient uptake, ROS detoxification, and ion homeostasis (Acharya *et al.*, 2024; Ma *et al.*, 2025; Mishra & Choudhary, 2026; Srivastava *et al.*, 2026).

(6) Halophyte-derived biostimulants: they are halophyte extracts or nanoparticles from halophyte extracts. Salt-tolerant plants produce unique metabolites enabling their extracts to act as biostimulants rich in stress-related metabolites (Jiang *et al.*, 2025).

(7) Agro-industrial by-product biostimulants: bio-based extracts derived from waste streams improving stress tolerance, root growth, antioxidants. Digestate-derived humic-like substances, fish hydrolysates, and other waste-extracts serve as sustainable, bio-based stimulants enhancing growth in saline soils (Zuzunaga-Rosas *et al.*, 2024).

(8) Multi-Component Bio-Based Biostimulants: combined plant + microbial formulations, mixed fungi + seaweed, biocatalyst (algal-fungal consortia). They are considered integrated blends of plant, animal, microbial compounds with synergistic effects against salinity. Many commercial formulations combine plant, microbial, and protein-hydrolysate components, with synergistic salinity-mitigating effects (Benito *et al.*, 2025; Wahid *et al.*, 2026).

Conventional and nano-enabled biostimulants in bio-saline farming: Nano-enabled biostimulants appear to offer more targeted, stable, and potentially more efficient salinity mitigation than conventional biostimulants or agronomic amendments in bio-saline farming, because nanocarriers can improve bioavailability, controlled release, shelf life, and site-specific delivery while reducing losses from degradation or runoff (Magnabosco *et al.*, 2023; Sow *et al.*, 2026). As mentioned before, the conventional approaches might include microbial inoculants, plant-derived extracts, protein hydrolysates, seaweed products, and mineral foliar inputs can still substantially improve root growth, ion balance, antioxidant defense, photosynthesis, and yield under salinity, as reported in many crops such as tomato (Zuzunaga-Rosas *et al.*, 2026), pepper (Silva *et al.*, 2025), onion (Nogueira *et al.*, 2025), rice (Lamlom *et al.*, 2025), and other studies, but their performance is often more variable across crop genotypes, soil types, doses, and timing (Sifola *et al.*, 2023). In addition, conventional biostimulants can improve soil health and reduce salinity indirectly, for example by increasing root length, aggregate stability, cation exchange capacity, and beneficial soil biology (Zuzunaga-Rosas *et al.*, 2026), whereas nano-enabled systems are still limited by regulatory uncertainty, field-scale validation gaps, cost, and safety concerns about long-term environmental persistence and human/soil impacts (Agrawal *et al.*, 2025). Conventional biostimulants are already practical and effective in many saline studies, but nano-enabled biostimulants are the more advanced platform for precision delivery and durability, provided their safety and real-

world performance are proven at scale (Elshayb *et al.*, 2022; Seleiman *et al.*, 2023; Edussuriya *et al.*, 2026; Sow *et al.*, 2026). A comparison of nano-enabled biostimulants and conventional approaches can be noticed in Table 4.

From previous studies, it can be concluded that nano-enabled biostimulants offer distinct mechanistic advantages over conventional formulations by bypassing plant cellular barriers, enhancing active ingredient permeability, and providing protective encapsulation against degradation, thereby ensuring controlled release under high-salinity stress. Despite this demonstrated laboratory efficacy, a substantial implementation gap remains between controlled experiments and field applications; complex soil matrices and fluctuating organic matter alter nanocarrier behavior in open systems. Consequently, concerns regarding environmental safety, operational feasibility, and high cost persist, highlighting the need for extensive, multi-season field trials to establish their long-term safety and economic viability. 5. Nanotechnology and plant biostimulants.

Nano-biostimulants: A standalone metal/metal-oxide nanoparticle acting as an inorganic elicitor is a nano-elicitor or nano-fertilizer, whereas a nano-biostimulant specifically involves nanocarrier-mediated delivery of bioactive organic compounds (e.g., chitosan-encapsulated plant extracts, nano-emulsions of seaweed extracts). Biostimulant is defined as "a formulated product of biological origin that improves plant productivity as a consequence of the novel or emergent properties of the complex of constituents, and not as a sole consequence of the presence of known essential plant nutrients, plant growth regulators, or plant protective compounds" (Yakhin *et al.*, 2017). Biostimulants are natural bioactive compounds having the ability to enhance plant growth and stress tolerance by promoting plant physiological and metabolic responses (Abdelhamid *et al.*, 2022; Di Sario *et al.*, 2025). The common used biostimulants may include humic and fulvic acids, seaweed extracts, protein hydrolysates, plant extracts and microbial inoculants (Tarafdar 2022). The main difference between conventional fertilizers and biostimulants might back to the main function of each one (Fig. 4). Beside the nutritional value, biostimulant benefits could touch improving nutrient-use efficiency, root architecture, water-use efficiency, and plant resilience to abiotic stresses (Abdelhamid *et al.*, 2022; Chhetri *et al.*, 2025). Plant biostimulants could be classified into the following groups: protein-based biostimulants, humic-based biostimulants, oligosaccharide-based biostimulants, metabolites-based biostimulants, inorganic substances, and microbial inoculants (Jiang *et al.*, 2024). Due to great challenges facing global agriculture, much more great efforts should be performed to overcome the main global problems including limited fertile land, rising food demand, and crop losses due to biotic and abiotic stressors. Nano-biostimulants are considered sustainable solution aiming to enhance delivery of nutrients and plant resilience along with reducing environmental stress (Sánchez-Campos *et al.*, 2026).

Several pathways could be used to produce nano-biostimulants, which mainly depend on the type of both nanoparticles (NPs) or nanomaterials (NMs) and biostimulant. In general, NPs and NMs could be considered as biostimulants because of their used in lower applied doses and having distinguished surface characterization to increase plant growth (Juárez-Maldonado *et al.*, 2019). Furthermore, several nanomaterials were reported to be biostimulant-like

effects such as, nano-selenium and glutathione (Alhammad *et al.*, 2023; Jia *et al.*, 2024), nano-chitosan and microalgae-based protein hydrolysate (Munaro *et al.*, 2024), nano-encapsulated biostimulant (Matthews *et al.*, 2025), hydroxyapatite-curcumin nanocomposite (Sánchez-Campos *et al.*, 2026), and carbon nanomaterials (CNMs; Raveena *et al.*, 2026). The mechanism of such nano-biostimulants mainly depends on the interplay role of both nanomaterial and biostimulant (Table 5).

Nano-carbon dots and carbon-nanotubes are considered biostimulant-like effects and can improve crop photosynthetic stress tolerance. Under salinity stress, CNMs have the protective impacts on the photosynthetic apparatus by modulating stomatal conductance, enhancing antioxidant enzyme, reducing ROS accumulation and stabilizing thylakoid membranes and pigments (Nasermoadeli *et al.*, 2026). Combined of halophyte-derived nanoparticles and biostimulants is considered one of the important kind of nano-biostimulants (Hanif *et al.*, 2023; Agrawal *et al.*, 2025). Application of halophytic-based NPs under salinity stress has shown many benefits for crop production by improving water efficiency, enhancing the plants' ion flux, reactive oxygen species detoxification, regulation of oxidation-reduction reactions, and hormonal signaling pathways under stress (Munir *et al.*, 2021). On the other hand, both NPs and biostimulants have become prominent in modern agriculture for a plenty of uses, ranging from mitigating various abiotic stresses (like salinity and drought) to improving nutrient efficiency (Agrawal *et al.*, 2025).

Green synthesis and bio-mediated nanomaterials:

Recently, a great progress in the field of nanobiotechnology has been achieved to be shifted toward eco-friendly and sustainable methods for synthesizing nanoparticles (NPs). Several biological agents have been applied in producing NPs through green and biological methods as promising natural bio-factories for NPs-synthesis such as mushrooms (Thakur *et al.*, 2026), plants (Kour *et al.*, 2026), bacteria (Ge *et al.*, 2024), fungi (Ahmad *et al.*, 2024; Sharma *et al.*, 2025), and algae (Akl *et al.*, 2024). These biological methods are considered a sustainable alternative to traditional physical and chemical processes due to their benefits as safety, cost-effectiveness, and environmental sustainability (Ghorbani *et al.*, 2026). As mentioned before, nanoparticles and nanomaterials can play role in supporting plant growth as a biostimulant (Garza-García *et al.*, 2023; Missaoui *et al.*, 2024). This confirmed by Ahmed *et al.*, (2025) through their study on producing green-Se-NPs using root extract of *Ferula assa-foetida* L. along with emphasizing the role of Se-NPs' biostimulant effects on seed germination of *Vicia faba* L. The role of green synthesized nanoparticles in mitigation of stressful plant under salinity stress was confirmed in Table 6. The common mechanism of green synthesized nanoparticle in ameliorating salinity stress might focus on the synergistic and efficient NPs in enhancing plant biological efficacy, thereby improving plant tolerance to salinity stress by increasing enzymatic antioxidants (ascorbic peroxidase, APX; catalase, CAT; superoxide dismutase, SOD; peroxidase, POD) activities under salinity stress, along with decrease malondialdehyde (MDA) content in plant compared with the control (Akhtar *et al.*, 2026). Finally, bio-based materials or biostimulants and biogenic nanoparticles can improve crop production in normal and stressful conditions (Tolisano & Del Buono, 2023).

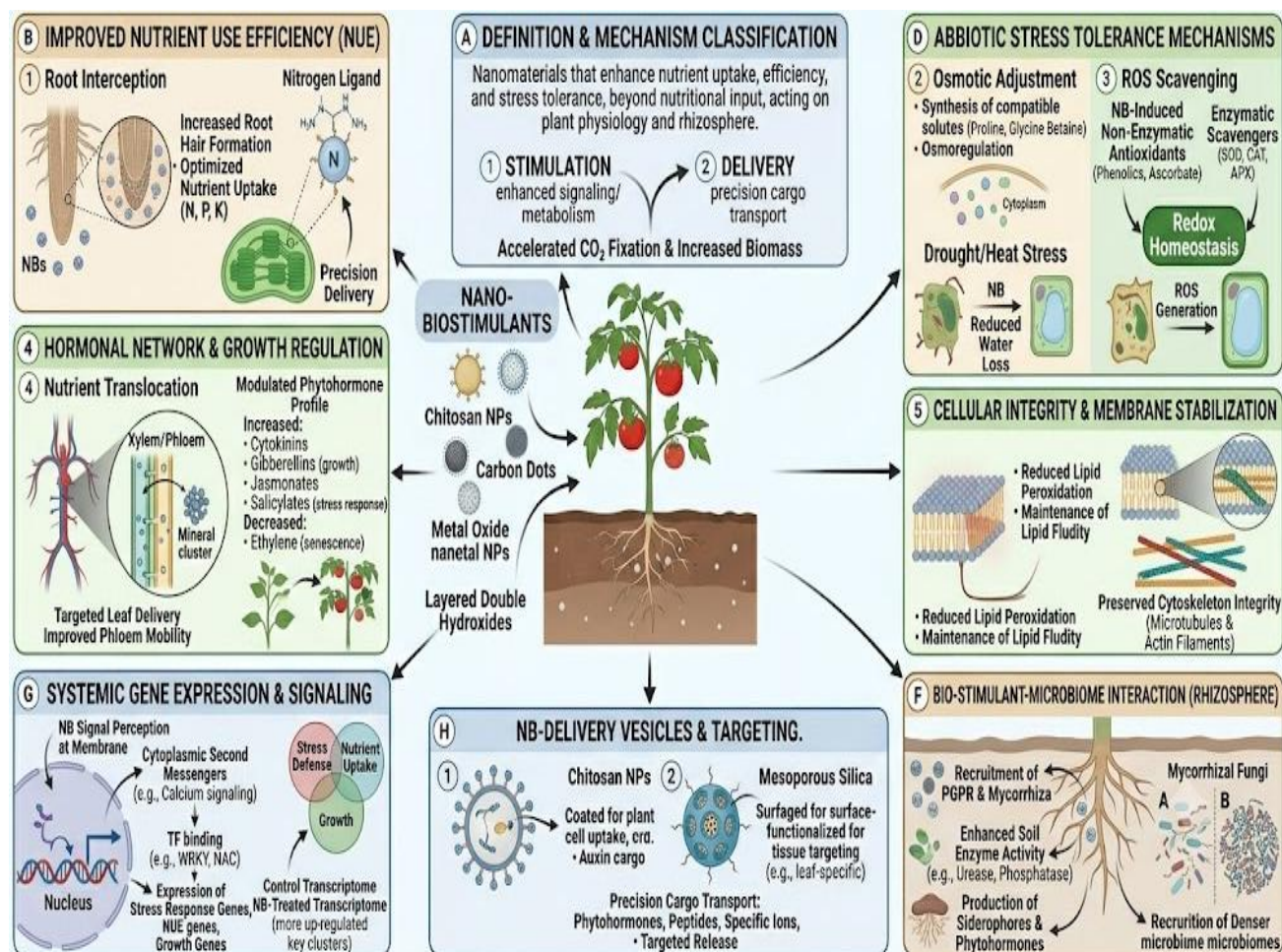


Fig. 4. Nano-biostimulants and their suggested mode of action.

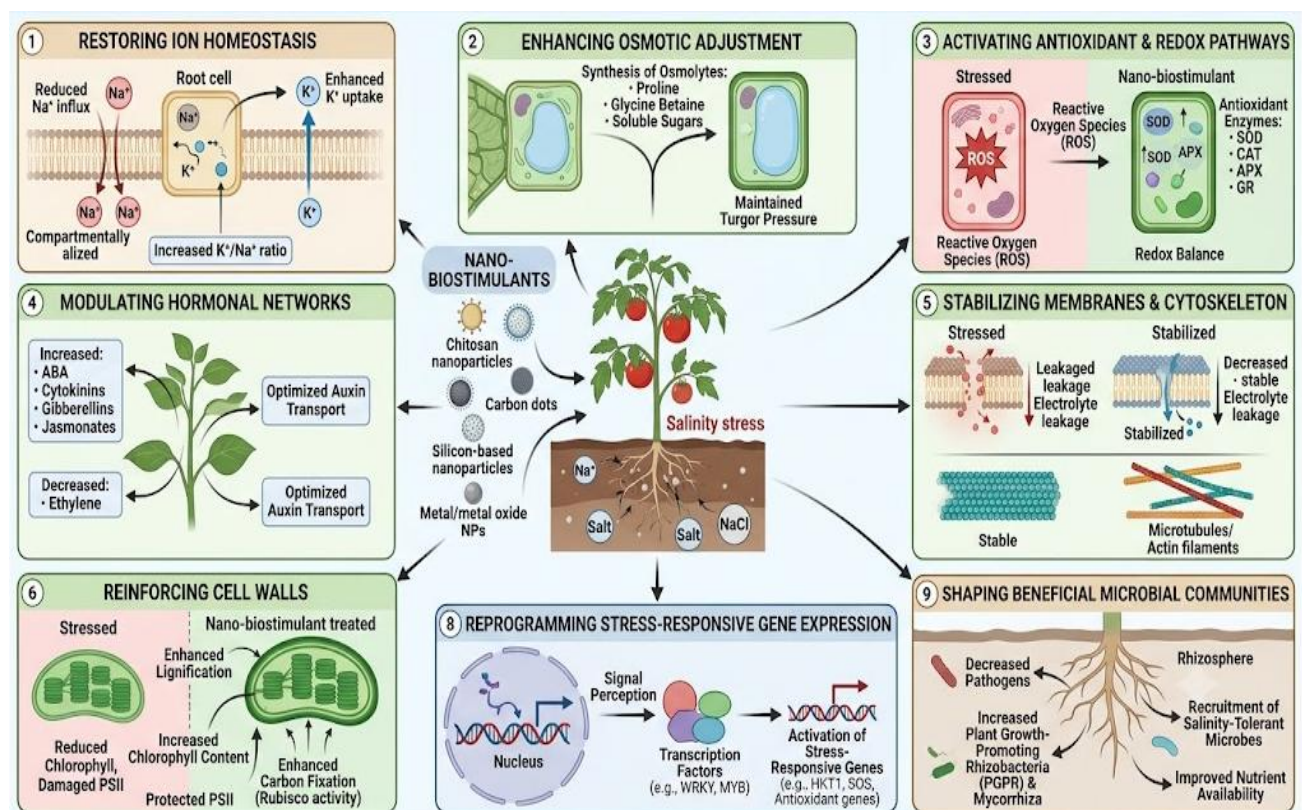


Fig. 5. The suggested mechanism of nano-biostimulants under salinity stress.

Table 5. A list of case study on nano-biostimulants and their impacts in different conditions

Plant species	Source of nanomaterial	Source of biostimulants	Main purpose of the study	References
Chili pepper (<i>Capiscum annuum</i>)	Moringa leaf extract nano-emulsion	Microbial inoculants (<i>Bacillus</i> MR3 and <i>Streptomyces</i> MR13)	Nano-encapsulated biostimulants improved plant growth and the postharvest quality of chili fruits	Matthews <i>et al.</i> , (2025)
<i>Raphanus sativus</i> L. and <i>Solanum lycopersicum</i> L.	Nano-hydroxyapatite	Curcumin powder	Nano-composites as nano-biostimulants for early-stage of tomato and radish development	Sánchez-Campos <i>et al.</i> , (2026)
Basil (<i>Ocimum basilicum</i> L.)	Algae-derived carbon quantum dots (CQD) at 2.5, 50 and 75 mg L ⁻¹	Biogenic synthesis of carbon from red algae (<i>Gracilaria corticata</i>)	Foliar CQD applied at 50 ppm increased basil photosynthesis by 45% and biomass by 30%	Nasemmoadehi <i>et al.</i> , (2026)
Damask rose (<i>Rosa damascene</i>)	Nano-silicon at 50, and 100 mg L ⁻¹	Brown seaweed (<i>Ascophyllium nodosum</i>) extract at 2 and 3 g L ⁻¹	Nano-biostimulant regulated negative impacts under salt stress (100 mM NaCl)	Seyed Hajizadeh <i>et al.</i> , (2023)
Wheat, barley, and oat	Nano-chitosan	Garlic extract at dose (<0.1%)	Nano-biostimulant as nano-priming agent increased metabolism and development compared with untreated seeds	Mondéjar-López <i>et al.</i> , (2024)
Cucumber (<i>Cucumis sativus</i> L.)	Nano-Selenium	Glutathione (GSH)	Nano-biostimulants of nano-Se and GSH protected cucumber plants <i>Bortyris cinerea</i> infection	Jia <i>et al.</i> , (2024)
Tomato (<i>Solanum lycopersicum</i> L.)	Foliar applied iron nano-complex at 0.2, and 0.4% w/v	Biostimulant Atonik (Nitrophenolate) at 125, and 250 ppm	Nano-biostimulants at 0.4% and 250 ppm improved growth of tomato seedling in greenhouse	Tavallali & Darvishzade (2025)
Tomato (<i>Solanum lycopersicum</i> L.)	Nano-NPK fertilizers at 40, 80, and 120 kg ha ⁻¹	Salicylic acid at 0.3%	Combined 80 kg ha ⁻¹ nano-NPK with 0.3% SA optimized yield and profitability	Guan <i>et al.</i> , (2026)
Henp (<i>Cannabis sativa</i> L.)	Si-Based phyto-couner hybrid	Flavonoid quercetin	Nano-biostimulant decreased salt stress (250 mM NaCl) symptoms by modulating the amount of soluble sugars	Guerriero <i>et al.</i> , (2021)
Tomato (<i>Solanum lycopersicum</i> L.)	Lectidim/chitosan-based nanoparticle formulations	Microalgae-based protein hydrolysate	Nano-biostimulant enhanced tomato growth- nitrogen fixation	Munaro <i>et al.</i> , (2024)

Table 6. Green synthesized of nanoparticle-mediated alleviation of salt stress.

Plant species	Nano-details	Salinity stress details	Main impacts	References
Mustard (<i>Brassica campestris</i> L.)	Green Se-NPs synthesized by grapes extract (30 mg L ⁻¹)	Salt stress (200 mM NaCl)	Modulated growth parameters and metabolic activities by controlling enzymatic antioxidant activities under salt stress conditions	Sarkar and Kalita (2022)
Pepper (<i>Capiscum annuum</i> L.)	Green Se- NPs (5, 10, 20 mg L ⁻¹) synthesized extract <i>Sterinbergia candida</i>	Salt stress (100 mM NaCl)	Reduced proline and MDA levels; boosting chlorophyll, carotenoids, antioxidant activity, and total phenolic content under stress	Kanber <i>et al.</i> , (2025)
Maize (<i>Zea mays</i> L.)	Green-engineered calcium-doped carbon nanospheres	Salt-affected soils in the field	Applied nano-composite alleviated NaCl toxicity and promoted the growth in saline soil	Javaid <i>et al.</i> , (2025)
Maize (<i>Zea mays</i> L.) seedlings	Green synthesized lignin nanoparticles (LNPs) (200 mg/L)	Salt stress (150 mM NaCl) as nano-priming	Mitigated NaCl-induced stress by reducing damages to guard cells, stomata & ultra-cellular structures	Javaid <i>et al.</i> , (2024)
Sweet potato (<i>Ipomoea batatas</i> L.)	Carbon-dot-NPs (CD NPs)	Salt stress (200 mM NaCl)	CD-NPs regulate ion homeostasis by enhancing K ⁺ /Na ⁺ balance and up-regulating key ion transporters	Zeb <i>et al.</i> , (2025)
Rapeseed (<i>Brassica napus</i> L.)	Green fluorescent carbon dots (CDs) at 90 mg L ⁻¹ CDs	200 mM NaCl at 1/2 MS medium	CDs improved Na ⁺ /K ⁺ balance by limiting Na ⁺ translocation, enhanced K ⁺ uptake, increased K ⁺ /Na ⁺ ratio; mitigated salt stress	Wang Y <i>et al.</i> , (2026)
Radish (<i>Raphanus sativus</i> L.)	Green magnesium oxide NPs (MgO-NPs) at 10-150 ppm	50, 100, and 150 mM NaCl in glass petri plates	Applied at 150 mg L ⁻¹ as nano-priming enhanced antioxidant parameters; osmo-protectant levels; radish salt stress tolerance	Gautam <i>et al.</i> , (2025)
Bottle gourd (<i>Lagenaria siceraria</i> L.)	Green ZnO-NPs at 250, 500 and 750 mg L ⁻¹	Salt stress (200 ppm NaCl)	Soil drenching by ZnONPs at 500 mg L ⁻¹ mitigated salt toxicity, increased total soluble sugars and maintained gas exchange parameters	Javeed <i>et al.</i> , 2023
Barley (<i>Hordeum vulgare</i> L.)	Green Cu-NPs at 25 and 50 mg L ⁻¹ from <i>Solenostemma argel</i> extract	Salt stress (100 and 200 mM NaCl) in plastic pots	Cu-NPs lower the accumulation of H ₂ O ₂ , osmolytes, MDA, flavonoids, and total phenol, while simultaneously enhancing the activities of antioxidant enzymes	Shaikhaldein <i>et al.</i> , (2024)
<i>Maerna oblongifolia</i> (Forsk.) A. Rich.)	Green Ag-NPs at 10, 20, and 30 mg L ⁻¹	Salt stress at 50, 100, and 200 mM NaCl in vitro	Applied Ag-NPs alleviate adverse impact of salt stress; ameliorate plant growth parameters and defense systems	Shaikhaldein <i>et al.</i> , (2022)

Abbreviations: NPs = Nanoparticles, MDA= Malondialdehyde

Table 7. Suggested mechanisms of nano-biostimulants in mitigation of salinity stress.

Mechanism(s)	Functional description(s)	Representative evidence from publications	References
Regulation of ion homeostasis	NMs maintain high K ⁺ /Na ⁺ ratios, reduce Na ⁺ uptake, enhance K ⁺ retention, and activate key ion transporters (SOS1/2/3, HKT1, NHX, and AKT)	Nano Zn/Si reduces apoplastic and symplastic Na ⁺ and improves K ⁺ retention ZnO-NPs restore K ⁺ and suppress Na ⁺ LNPs upregulate HKT1, NHX, CBL genes Se-NPs + MWCNTs improve Na ⁺ /K ⁺ balance.	Shoukat <i>et al.</i> , (2025); U'padhyay <i>et al.</i> , (2025)
Osmotic adjustment and water balance	Nano-biostimulants increase osmolytes (proline, sugars, GB), enhance aquaporin expression, regulate water uptake, and stabilize cell hydration	ZnO-NPs reduce osmotic stress markers LNPs increase osmolytes CNTs and other NPs modulate aquaporins improving water flow; MZ-ZnO-NPs rebalance osmo-protectants.	Baksi <i>et al.</i> , (2025); Du <i>et al.</i> , (2026)
ROS scavenging and antioxidant activation	Nanoenzymes and nano- formulations detoxify ROS, boost enzymatic (SOD, CAT, POD, APX) and non-enzymatic antioxidants, and restore redox homeostasis	MXenzymes strongly scavenge ROS; Cs-Se-NMs boost SOD/CAT/POD Cu ₂ N-CDs increase antioxidant flux; Ag-NP nano-priming boosts SOD/CAT/GPX LNPs reduce MDA and oxidative injury	Fang <i>et al.</i> , (2024); Han <i>et al.</i> , (2025)
Regulation of phytohormones	NMs modulate ABA, cytokinins, and melatonin pathways to regulate stomata, osmotic stress, photosynthesis, and stress signaling	Nano-melatonin ZnO regulates ABA/MT-linked antioxidant and ion pathways Nano-biostimulants upregulate cytokinin biosynthesis under salinity Nano-enabled signaling affects Ca ²⁺ –hormone crosstalk	Mohamed <i>et al.</i> , (2025); Yang <i>et al.</i> , (2025)
Cytoskeleton and membrane stability	Nano-biostimulants maintain actin/microtubule integrity, protect membranes, and stabilize transporter localization.	Cytoskeleton disruption under NaCl is mitigated by nano-interactions Membrane protection via reduced ROS and improved lipid stability in several applied NPs	Gan <i>et al.</i> , (2026); Jamei <i>et al.</i> , (2026)
Cell wall integrity and remodeling	NMs enhance lignin/cellulose metabolism, strengthen wall architecture, and reduce Na ⁺ -induced structural damage	LNPs protect guard cells and ultrastructure; LCNF-Se-NPs enhance lignin and cellulose Nano-Si strengthens wall pectin/cellulose networks	Javaid <i>et al.</i> , (2024); Dadpour <i>et al.</i> , (2026)
Photosynthesis optimization	NMs protect chlorophyll, PSII, and carbon metabolism, improving gas exchange under salinity	MZ-ZnO-NPs improve chlorophyll CeO ₂ -NMs enhance photosynthetic efficiency Cu ₂ N-CDs increase pigment content	Liu <i>et al.</i> , (2022); Esgici <i>et al.</i> , (2026)
Gene expression and metabolic reprogramming	Nano-biostimulants induce salt-responsive genes (NHX, HKT, MAPKs, and CBLs), enhance secondary metabolites & modulate transcriptomic stress pathways	LNPs upregulate NHX, HKT, and MAPK Cs-Se-NMs upregulate oxidative and MAPK pathways MXenzymes alter hormone and energy-metabolism genes	Zhang <i>et al.</i> , (2024); Siddiqi <i>et al.</i> , (2025)
Microbiome modulation	NMs shift rhizosphere bacterial communities, enhancing beneficial halotolerant microbes	CeO ₂ -NMs increase PGP rhizobacteria; Cs-Se-NMs remodel microbial communities	Qi <i>et al.</i> , (2026); Manzoor <i>et al.</i> , (2025)

Abbreviations: NMs = Nanomaterials; HKT1= High-affinity potassium transporter 1, NHX= Na⁺/H⁺ Antiporter family, CBLs= Calciuretin B-like proteins; SOS1= Salt overly sensitive 1; AKT= Arabidopsis K⁺ transporter; MWCNTs= Multi-walled carbon nanotubes; CNTs= Carbon nanotubes; MAPKs= Mitogen-activated protein kinases; LNPs= Lipid nanoparticles; GB= Glycine betaine; MZ-ZnO-NPs= Metronidazole-loaded zinc oxide nanoparticles; MXenzymes = MXenes and nanozymes; ABA/MT-linked= Abscicic acid-melatonin linked

Mechanisms of nano-biostimulants under salinity stress:

The suggested mechanism of nano-biostimulants may rely on the following approaches enhanced root penetration and systematic cellular delivery, activation of enzymatic antioxidants (APX, CAT, SOD, POD) and reactive oxygen species (ROS) scavenging cascade, regulation of osmo-protectant through regulation of soluble sugars, proline, and glycine betaine (GB) synthesis, modulation of photosynthetic machinery and light-harvesting efficiency, and regulation of ion transporters and channels such as salt overly sensitive 1 (SOS1), non-selective cation channels (NSCCs) and high-affinity potassium transporter 1 (HKT1) to maintain mainly K^+/Na^+ ratios (Table 7). Collectively, the previous approaches emphasize that biogenic nanoparticles can mitigate stress of salinity in several studied plants through ion balance, integrated regulation of antioxidant defense, and hormone-mediated gene expression (Islam *et al.*, 2026).

What are the mechanisms of nano-biostimulants in mitigation of salinity stress? It is noticed that the mode of action of nano-biostimulants comes from these compounds themselves. Nano-biostimulants combine nanoparticles (NPs) with biostimulant compounds to mitigate salinity stress by acting on cellular homeostasis, signal transduction, ion transport, antioxidant defense, and soil–plant–microbiome interactions. In brief, nano-biostimulants can mitigate salinity stress through integrated, multi-scale mechanisms, including (1) restoring ion homeostasis, (2) enhancing osmotic adjustment, (3) activating antioxidant and redox pathways, (4) modulating hormonal networks, (5) stabilizing membranes and cytoskeleton, (6) reinforcing cell walls, (7) improving photosynthesis, (8) reprogramming stress-responsive gene expression, and (9) shaping beneficial microbial communities (Fig. 5).

Field-scale adoption, nanotoxicity, environmental safety, and regulatory constraints:

Nano-biostimulants appear promising in bio-saline farming, but field-scale adoption is still limited and must be balanced against dose-dependent nanotoxicity, soil-microbe effects, and unresolved long-term environmental fate. Adoption is moving from proof-of-concept toward field use, but it is not yet mature, as the field evidence is positive in saline and semi-saline systems, yet the literature repeatedly warns that nano-biostimulants need dose control, standardized formulations, multi-site field trials, and formal ecotoxicological assessment before they can be considered broadly safe and scalable in bio-saline farming (Mansi & Danai, 2025; Mashabela *et al.*, 2025). Concerning field-scale performance, field and on-farm studies show yield and stress-tolerance gains from biostimulants and some nano-enabled products, including saline or salt-affected systems such as wheat, rice, tomato, potato, mango, and barley (Izquierdo *et al.*, 2025). These field studies are important to indicate practical potential, especially in salt-stressed and marginal soils. About the field application routes, both foliar and soil application are used (e.g., foliar nano-zinc, nano-boron, nano-silica, and other nano-products) improved growth or yield in multiple studies, while soil application sometimes performed best in meta-analysis and field trials as may suggest no single delivery

route is universally superior; site-specific optimization is needed (Li *et al.*, 2022). Regarding nanotoxicity and safety, excessive or poorly designed NPs can cause phytotoxicity, genotoxicity, oxidative stress, growth inhibition, and adverse soil/aquatic effects; toxicity depends on size, dose, surface chemistry, and environment (Akhter *et al.*, 2025). Safety is a central barrier to broad deployment in nano-biostimulants (Noman *et al.*, 2025). What about the knowledge gaps in nano-biostimulants? To explain why adoption remains cautious despite positive results, multiple reviews say most evidence is still under greenhouse or lab-based, with scarce multi-location field validation, limited long-term ecotoxicology, and weak standardization/regulation (Carillo, 2025; Khurshid *et al.*, 2026).

What about the environmental safety and regulations of nano-biostimulants? Nano-biostimulants in bio-saline farming are promising but not yet broadly environmentally cleared or regulation-ready. Previous studies showed the main constraints of nano-biostimulants safety may back to soil-microbiome disruption, uncertain environmental fate, dose-dependent phytotoxicity, and weak/uneven regulatory frameworks (Durgude *et al.*, 2026). The main barrier is not proof of benefit, but proof of safe, repeatable use across soils and salinity conditions. Nano-biostimulants can help bio-saline farming, yet their wider deployment is constrained by inconsistent ecotoxicology, potential microbiome harm, and regulatory systems that are still catching up (Kumari *et al.*, 2023). What constrains adoption? Environmental safety is not settled, as reviews say terrestrial risk assessment is still in its infancy, environmental concentrations are hard to estimate, and long-term impacts on soil life remain uncertain (Shah *et al.*, 2022; Kumari *et al.*, 2023). Soil microbiome effects are a central concern: nano-ZnO, nano-TiO₂, nanosilver, and other nanomaterials can reduce microbial biomass or shift community composition, and can interfere with N cycling and decomposition (Shah *et al.*, 2022).

Environmental fate and uptake of nano-biostimulants are still uncertain. Many studies reported about the aggregation, sedimentation, mobility, dissolution, translocation to groundwater, and accumulation in edible tissues as unresolved or variable issues (Khan *et al.*, 2025). Nano-biostimulants in bio-saline farming appear promising but not yet fully de-risked. Previous studies suggested that they can improve salt tolerance and productivity, but environmental safety remains constrained by unresolved questions about long-term fate, persistence, accumulation, and effects on soil biota, nutrient cycling, and ecosystem functioning (Magnabosco *et al.*, 2023). Safety is also dose- and formulation-dependent, meaning outcomes vary with nanoparticle type, size, surface chemistry, and application route (Khepar *et al.*, 2024). Seed nano-priming is presented as a lower-material, potentially lower-risk option than foliar or soil/root delivery (Özmen *et al.*, 2026). On the regulatory side, nano-biostimulants sit in an evolving and fragmented legal space, with gaps in standardization, safety testing, and harmonized approval pathways across regions, so compliance planning and field validation are still essential before broad deployment (Das & Dutta, 2026).

Conclusion

Under climate change, soil salinization increases year by year, posing a significant stress on global food security and sustainable agriculture. Thus, the bio-saline approach is a promising strategy for mitigating salinity stress on crops. Furthermore, the integration of nanotechnology into bio-saline farming represents a supportive strategy in addressing soil degradation. By converting complex physiological interventions into scalable agricultural solutions, nanotechnology helps manage the constraints of high-salinity environments. It provides precise biochemical tools that can enhance the potential of marginal lands, helping bio-saline farming evolve into a more resilient pillar of modern agriculture. Nano-enabled strategies, including nano-biostimulants, improve plant performance under salinity by restoring ion homeostasis, enhancing osmotic balance, activating antioxidant defenses, stabilizing cellular structures, and modulating hormonal pathways. Complementing this, nano-enabled soil and water management integrates nano-amendments, nano-fertilizers, and nano-biofertilizers to improve soil structure, nutrient availability, and water quality in saline environments. However, the sustainable deployment of these approaches requires careful evaluation of potential risks, including nanotoxicity, environmental fate, soil accumulation, impacts on non-target microflora, production scalability, and regulatory frameworks. Future research should prioritize long-term field-scale validation, dose optimization, standardized formulations, and life-cycle assessments to ensure the safe and effective application of nano-enabled technologies in bio-saline agriculture.

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