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Review

Nano-Management Approaches for Salt Tolerance in Plants under Field and In Vitro Conditions

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Abstract: Soil salinity is a serious global problem that threatens a high percentage of the global soils. Salinity stress can create ionic, oxidative, and osmotic stress, along with hormonal imbalances, in stressful plants. This kind of stress was investigated on agricultural productivity at different levels, starting in vitro (plant tissue culture), through hydroponics, pots, and field conditions. Several approaches were studied for managing salinity stress, including using traditional materials (e.g., gypsum, sulfur), organic amendments (e.g., compost, biochar, chitosan), and applied manufactured or engineered nanomaterials (NMs). Application of nanomaterials for ameliorating salinity stress has gained great attention due to their high efficiency, eco-friendliness, and non-toxicity, especially biological nanomaterials. The application of NMs did not only support growing stressful plants under salinity stress but also increased the yield of crops, provided an economically feasible nutrient management approach, and was environmentally robust for sustainable crop productivity. Nano-management of salinity may involve applying traditional nano-amendments, biological nanomaterials, nano-enabled nutrients, nano-organic amendments, derived smart nanostructures, and nano-tolerant plant cultivars. Producing different plant cultivars that are tolerant to salinity can be achieved using conventional breeding and plantomics technologies. In addition to the large-scale use of nanomaterials, there is an urgent need to address and treat nanotoxicity. This study aims to contribute to this growing area of research by exploring different approaches for nano-management of current practices under salinity stress under field and in vitro conditions. This study also raises many questions regarding the expected interaction between the toxic effects of salinity and NMs under such conditions. This includes whether this interaction acts positively or negatively on the cultivated plants and soil biological activity, or what regulatory ecotoxicity tests and protocols should be used in research.

Keywords: nano-biochar; nano-gypsum; nanoparticles; nanotoxicity nanofarming; plant growth regulators; salt stress

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1. Introduction

The rising salinity in soil and water is considered a serious threat to global agricultural productivity, especially in arid and semi-arid regions [1], which account for more than 833 million ha, or 8.7% of the global soils [2]. Salinity stress represents a vital abiotic stress that causes significant damage to agro-production due to the high accumulation of soluble salts, mainly sodium chloride (NaCl), in soil and water [3,4]. Global food security could be strongly linked with salinity risk due to the detrimental effects of salt on all plant processes (i.e., physiological, morphological, and biochemical attributes) and decreasing the production of food [5,6]. The main mechanism of salinity stress includes both osmotic and oxidative stress, leading to the production of reactive oxygen species (ROS), ions, and hormonal imbalance [7]. Direct and indirect results can be noticed under salinity stress, which represent the decline of several biological plant activities and reduce the final crop yield [8]. There are several strategies to cope with salinity stress, starting with developing crop cultivars tolerant to salinity through applying traditional breeding methods [9], genetic and molecular techniques [10–12], nutrients/nanonutrient management strategies [13,14], and using organic amendments or hormonal regulators [15–17]. As a result of the negative effects of salinity on crop growth and/or productivity, a notable reduction was noticed for many crops, such as safflower [1], rice [2], and maize [18]. Their productivity decreased by 47, 40, and 31%, respectively, when plants were exposed to salinity of 15 dS m^{-1}, 300 mM NaCl stress, and 3000 ppm irrigation water, respectively.

Agro-productivity is the production of plants, animals, and microbes in the agriculture sector, which should be investigated under different conditions to obtain the desired production, particularly under stressful conditions. The management of agricultural production mainly depends on domain stress, which may include abiotic (e.g., salinity, drought, heat, and waterlogging) and biotic (e.g., diseases of organisms) stresses [19,20]. Nano-management has great potential for solving several agro-problems at the farm level through nano-farming [21]. Each agricultural practice may face a problem during agro-production, which can be managed by applying nanomaterials such as nanofertilizers [22,23], nanopesticides or nano-agrosomes [24], nanosensors for precision farming [25,26], sustainable agriculture [27], and improving conventional agricultural systems [28]. It seems that almost all agricultural practices on the farm were nano-automated by applying different forms of nanomaterials, as confirmed by recent reports [21,26,29–31]. It is worth mentioning that the main approaches to nano-management of salinity may include applying the traditional nano-amendments (nano-gypsum, nano-hydroxyapatite, nano-sulfur, etc.), nano-enabled nutrients (nano-Se, nano-silica, nano-TiO_2, nano-ZnO, nano-CuO, etc.), biological nanomaterials (mainly biological nano-agrochemicals), nano-organic amendments (nano-biochar, nano-compost, nano-chitosan, etc.), derived smart nanostructures, and nano-tolerant plant cultivars [8,11,29,31].

The agriculture sector is the unique field that supplies humanity with food and raw materials for energy, construction, and textile industries, besides the pharmaceutical industry [21]. Agriculture faces many problems, including climate change, urbanization, decreasing land holding, soil degradation, biodiversity decline, unsustainable use of natural resources, excessive use of agrochemicals, and air pollution [28,32,33]. Agro-practices mainly depend on the kind of farming, which differs from traditional to modern farming systems due to many factors, such as the intensive use of agrochemicals, efficiency, agrotoxicity, sustainability, and their impacts on targeted and non-targeted organisms in agroecosystems [34]. Nanofarming may present a sustainable solution through applying nanomaterials to different agro-practices, such as precision nano-farming using nanosensors to detect crop pathogens [25], nanorobotics, and nano-barcodes for enhancing crop productivity [28]. In addition, tremendous applications of nano-agro-tools were extensively implicated in many fields, such as gene transfer [35], nano-treatments of agro-wastes [36], nano-priming [37,38], nano-treatment of wastewater management [39], and nano-agrochemicals [40,41]. Furthermore, farmers, policymakers, and scientists are constantly searching for innovative methods or techniques to overcome existing agro-challenges [42]. There are several options for conducting experiments on such agro-practices, ranging from controlled laboratory and greenhouse experiments to field conditions.

Therefore, this review highlights the role of nanomaterials/nanoparticles in different farming practices under different possible experimental conditions, especially under salinity stress. This study also discusses the available approaches to nano-management in farming under salinity stress, with a special focus on applying nano-agrochemicals (nanofertilizers and nanopesticides), nano-soil amendments, nano-biofertilizers, nanocomposites, and in vitro nano-management. Nano-management of farming practices under salinity toxicity conditions will also be reported. In addition, this study will also compare our findings with other published studies related to the management of salinity under different conditions.

2. Salinity Stress Features and Its Problems

Soil salinity refers to the presence of water-soluble salts (mainly Na^+, Ca^{2+}, Mg^{2+}, sulfates, chlorides, carbohydrates, and bicarbonates). Soil salinization is the process of increasing the accumulation of salt content in soil due to higher temperatures and/or climate change [43,44]. Soil salinity and alkalinity are common features of salt-affected soils, besides sodic and saline-sodic soils, which refer to an excess of Na^+ among exchangeable cations in soil solution [45]. Primary salinization refers to the weathering process of parent materials and the high-water table or the gradual withdrawal of an ocean or seawater seepage towards delts, whereas secondary salinization is anthropogenic processes like irrigated cropping systems [46–48]. General causes of soil salinity may include (1) dry climates and low precipitations; (2) poor drainage or waterlogging; (3) irrigation with salt-rich water; (4) raised water tables; (5) sea-level rise through seepage into deltas; (6) seawater submergence; and (7) intensive and inappropriate application of fertilizers [49]. Common features of soil salinity include waterlogging and damp areas, whitening of the soil surface/ground, increased water level in furrows, deterioration of roads, buildings, etc., white or dark circles around water bodies, and bare soils due to dead plants. The main problems of soil salinity may include impairing plant growth and development due to excessive uptake of Na^+ and Cl^- ions, then causing water stress, cytotoxicity, and nutritional imbalance [50].

Soil salinity stress has distinguished effects on cultivated plants in morphological, physiological, biochemical, and molecular attributes. Generally, the main stress of salinity on plants is represented by both osmotic and ionic stress (Figure 1). Due to the high soluble ions of Na^+ and Cl^- in soil, plants can act through signal transduction to avoid this stress as much as possible. Concerning the plant morphological, biochemical, and physiological attributes, they may include (1) a decrease in shoot and root growth, biomass, and crop production; (2) nutritional disorder due to low K/Na ratio and ionic homeostasis; (3) a decrease in photosynthetic activity and water uptake; (4) increased ROS generation, antioxidant enzymes, and proline; (5) impaired regulation of aquaporins and stomata; (6) impaired water and nutrient balance; (7) inhibited seed emerging and reduced fruit size [46–48]. Molecular attributes of stressful plants under salinity involve oxidative damage to various cellular components such as proteins, lipids, mitochondria, and DNA. Several recent studies reported the response of stressful plants to salinity by regulating the pathways of functional proteins [51], by root exudation [52], by initiating signaling pathways to re-establish cellular homeostasis [53], or by modulating some metabolites [54].

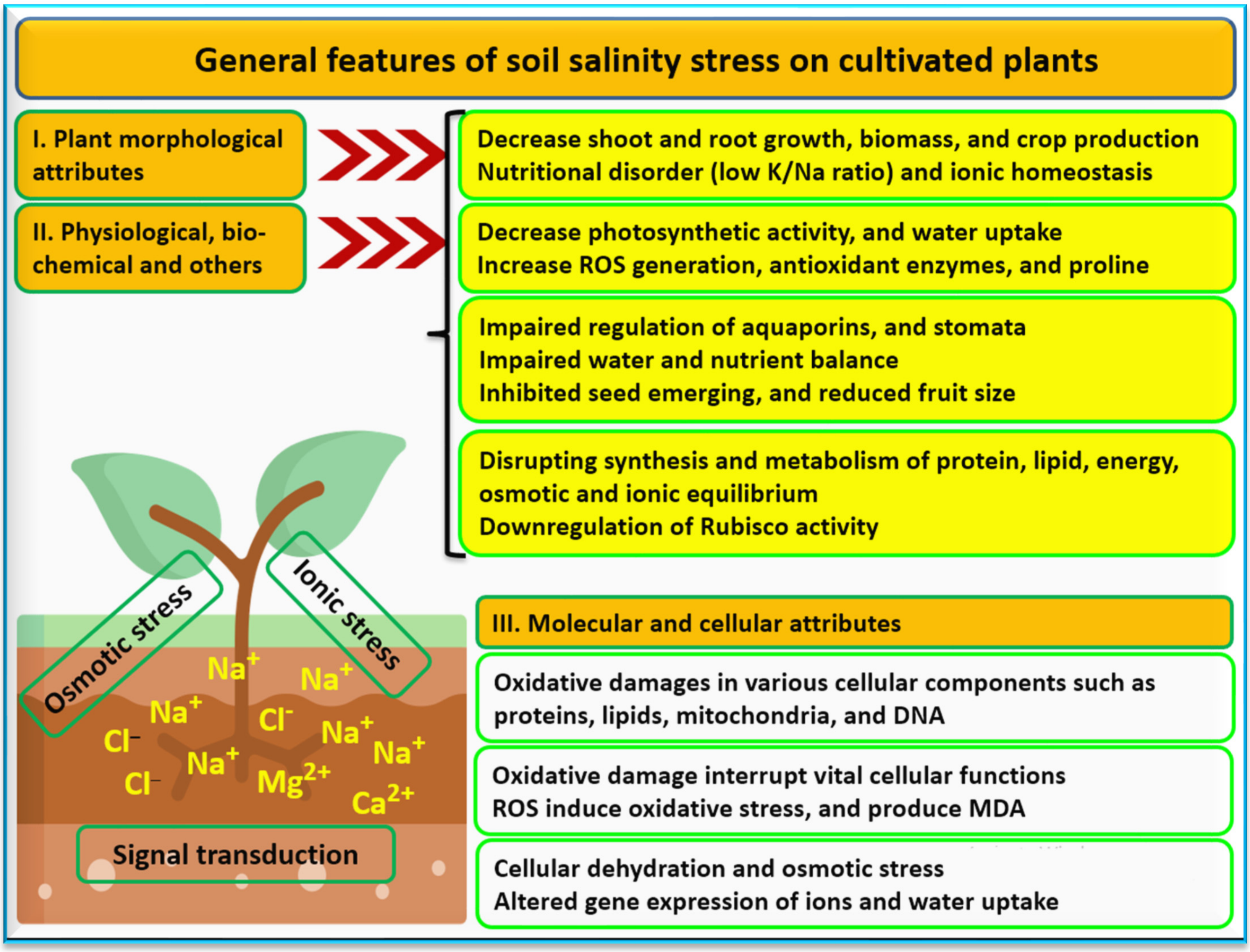

Figure 1. The main impacts of soil salinity stress on cultivated plants. These stresses involve morphological, physiological, biochemical, and molecular attributes. They can also cause osmotic and ionic stress on cultivated plants due to the high soluble anions of Na and Cl, which lead to the response of these plants to avoid this stress through signal transduction. RubisCo, ribulose bisphosphate carboxylase oxygenase; MDA, malondialdehyde; ROS, reactive oxygen species. Sources: from different refs., referring to the text.

3. Salinity and Productivity of Cereal Crops

As mentioned before, agriculture has several practices that have changed from traditional to modern agricultural practices. These practices need to focus on the possibility of increasing their efficiency in using agrochemicals while lowering their threat to the agroecosystem (Figure 2). This approach may reflect on crop productivity under salinity stress. In this section, the productivity of cereal crops is of importance to be highlighted due to their potential for global food security as a main source for 50% of the human protein and energy requirements [6]. The productivity of cereal crops (maize, wheat) under salt stress limits global food security, particularly under climate change, whereas other cereal crops (mainly paddy rice, barley, and sorghum) are moderately tolerant to salinity stress [55,56]. Management of soil salinity on cereal crops can be achieved by applying many agronomic practices, such as compost and zeolite [55], biotechnology approaches [6], and nano-approaches [57]. Among cereal crops, rice (*Oryza sativa* L.) feeds more than half of the world's population, whereas Asia produces and consumes around 90% of rice [58]. The tolerance of rice to soil salinity depends on the cultivars, the salinity level in the soil used, and the cultivation method (paddy, lowland, or upland rice) [59], which can impact not only rice productivity but also the nutritional value of harvested rice [60]. The main reason for salinity damage in cultivated rice may be due to sodium salts, which cause oxidative stress, alter cell metabolism, inhibit photosynthesis, and reduce grain yield and quality [59,61]. On the other hand, many applied materials or agro-practices with a focus on nanomaterials like chitosan-NPs have been used to mitigate salinity stress [58,62].

Comparison item	Conventional agro-practices	Modern agro-practices	Nano-based agro-practices
Agro-system type	Traditional system on agrochemicals	Organic system, less or no agrochemicals	Nano-agrochemicals
Fertilizer type	Mineral fertilizers	Organic/biofertilizers	Nano-fertilizers
Soil quality (Sustainability)	Pollutants problem from chemicals (NON)	Less problematic due to less chemicals (Yes)	Should less problem depending on dose (Yes)
Agrochemicals used	Used in a high amount	Less amount of minerals	Less nano-agrochemicals
Soil nutrient content	Less content of nutrients in soil	High soil content of nutrients	Soil content of nutrients maybe high
Practice efficiency	Poor efficiency	High efficiency	Exceptional high
Target of used agro-chemicals	Agrochemicals are non-targeted	Agrochemicals are non-targeted	Agrochemicals are should be targeted
Stability of used agro-chemicals	Agrochemicals are very less stability	Agrochemicals are in a better stability	Agrochemicals are in a good stability
Cost of practice	Very costly in a large quantity	These practices use cost-effective	Cost-effective used in minimum quantity
Agro-toxicity	Very hazardous or high risk of toxicity	These practices minimum toxicity	Green NMs are not toxic

Figure 2. Comparison among traditional, modern, and nano-based agro-practices used for increasing agriculture productivity. The comparison parameters may include soil quality, the efficiency of applied agro-practice, the suggested toxicity to the soil and environment, and the suggested usage amounts of agrochemicals. Sources: From different refs., referring to the text.

4. Nano-Management of Farming under Salinity Stress

Nanotechnology, as one of the largest growing technologies in the world, is considered a sustainable approach for overcoming several challenges in both the agroecosystem and the environment [63,64]. Many nano-applications in agriculture through different nanotools were confirmed, such as nanofertilizers, nanosensors, nano-amendments, and nano-pesticides, which have successfully transformed conventional farming methods into precision farming [42]. Several nano-formulations of traditional agricultural inputs, including mainly conventional fertilizers and pesticides, have been transformed into nanofertilizers and nanopesticides [65]. At the farm level, farmers are seeking to improve their agricultural practices by using nano-based materials (mainly fertilizers and pesticides), which can promote the efficiency and productivity of cultivated crops, especially under stress [21,42]. Some common nanomaterials that can be applied in agriculture for crop production are listed in Figure 3, which also shows the positive and presumed negative impacts of these nanomaterials, and their application methods are presented as well. Generally, many negative effects of applied NMs might be on crop production, including inhibited uptake and transport of both water and nutrients, generating ROS, causing dose-dependent genotoxicity, DNA damage, and cell death [66]. Soil salinity can also be managed by using many sources of nanomaterials [47,67] (Figure 4).

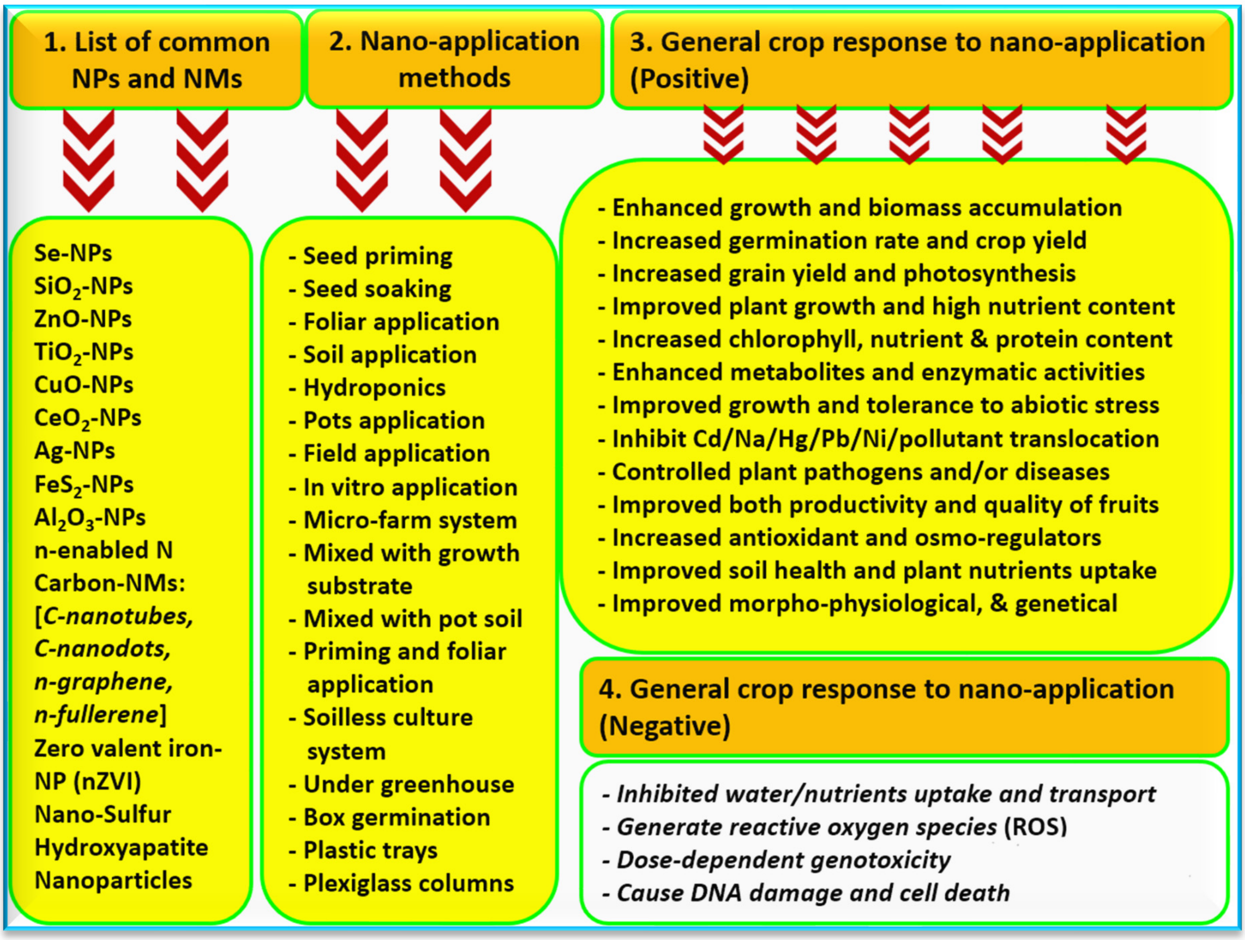

Figure 3. A list of the most common nanoparticles (NPs) and nanomaterials (NMs) (part 1) that can be applied in agriculture for crop production through different methods (part 2). The positive and presumed negative impacts of these nanomaterials and their application methods are presented as well in parts 3 and 4. Sources: from different refs., referring to the text.

Nano-management of soil salinity can be achieved through many approaches, which mainly aim to enhance plant growth, its tolerance to salinity stress, and improvements in soil structure and quality [47,67]. These approaches may include applying traditional methods (nano-gypsum, nano-hydroxyapatite, nano-sulfur, etc.), nano-nutrients (nano-calcium, nano-selenium, nano-silicon, nano-ZnO, etc.), nano-amendments (nanobiochar, nano-compost, nano-chitosan, etc.), and nano-halophytes and salt-tolerant genotypes [66,68–71]. Carbon nanomaterials against stress on crops were also investigated, including many carbon-NMs such as carbon nanotubes, carbon nanodots, nanographene, and nanofullerene [72]. Furthermore, zero-valent iron-NP (nZVI) and nanobiofertilizers, or biological nanofertilizers, are also effective approaches to mitigating soil salinity [39,73,74]. More details will be presented in the following sub-sections:

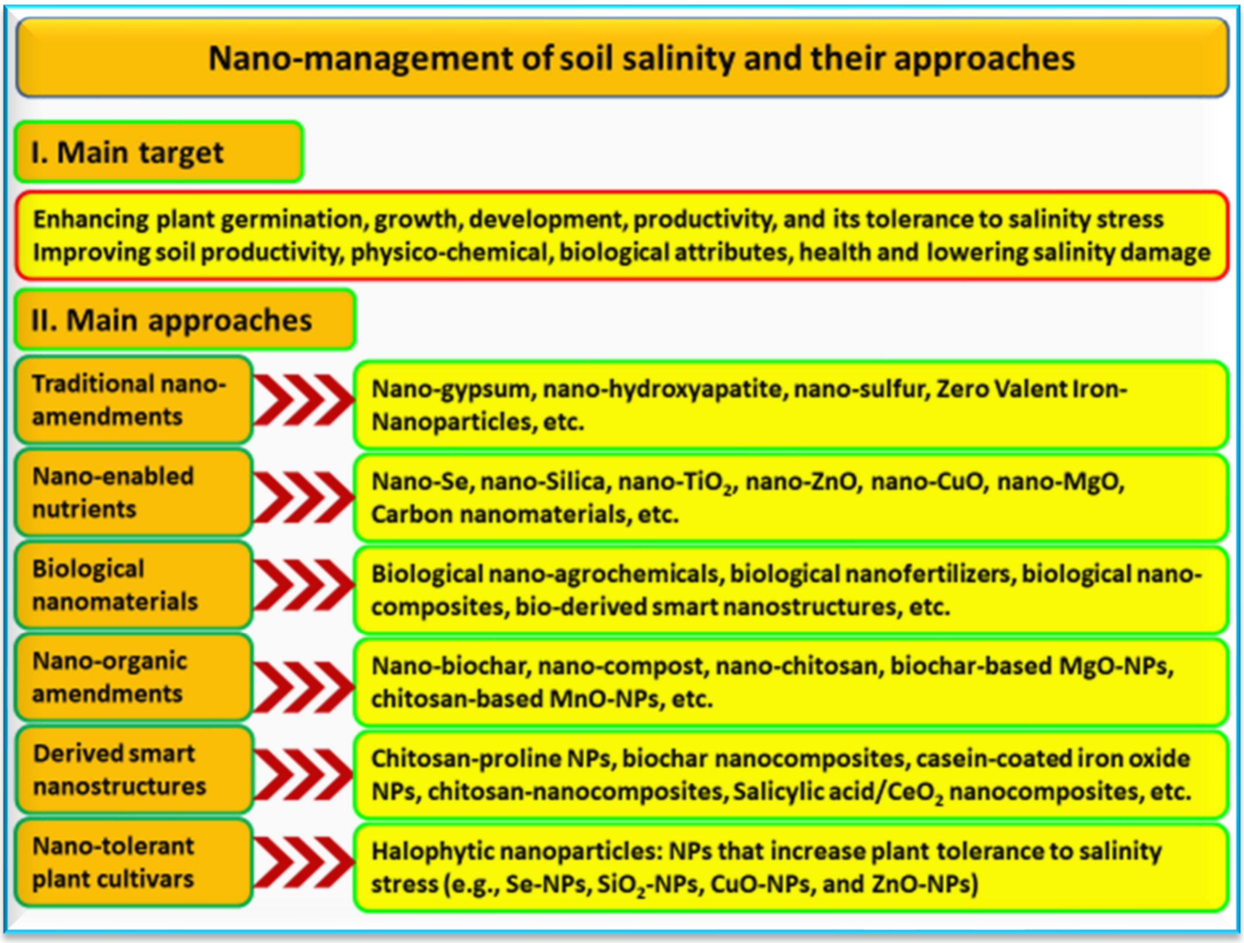

Figure 4. The main target of nanomanagement of soil salinity (part I) and different suggested approaches (part II), which include traditional, biological, and other derived smart nanomaterials. Sources: [47,67].

4.1. Nano-Agrochemicals

Due to the incredible increase in global population and limited crop production, more than 800 million people are currently undernourished, and this will reach more than 2 billion people by 2050 [75]. In this situation, there is an urgent need to increase global agro-production by more than 70% in the next few decades, which requires more applications of agrochemicals (mainly fertilizers, pesticides, and plant growth regulators) for higher crop production to meet this global demand [76]. Every year, there is an over 2.5% increase in the global market of agrochemicals, which are directly linked to crop protection, as reported in 2017, to over 55 billion dollars [75]. These agrochemicals may be used for protecting cultivated crops from diseases (pesticides) or for increased crop production (chemical fertilizers). Several studies confirmed the potential of nano-based agrochemicals in agriculture (mainly in soil and plants) and the main factors controlling the fate and uptake of nano-agrochemicals by plants from soil (Figure 5). These studies focused on the toxicity of nano-based agrochemicals on non-target aquatic species [75], on plant-associated microbiomes [77], smart agrochemical nanomaterials [78,79], and their potential risk assessment for human health [55,80].

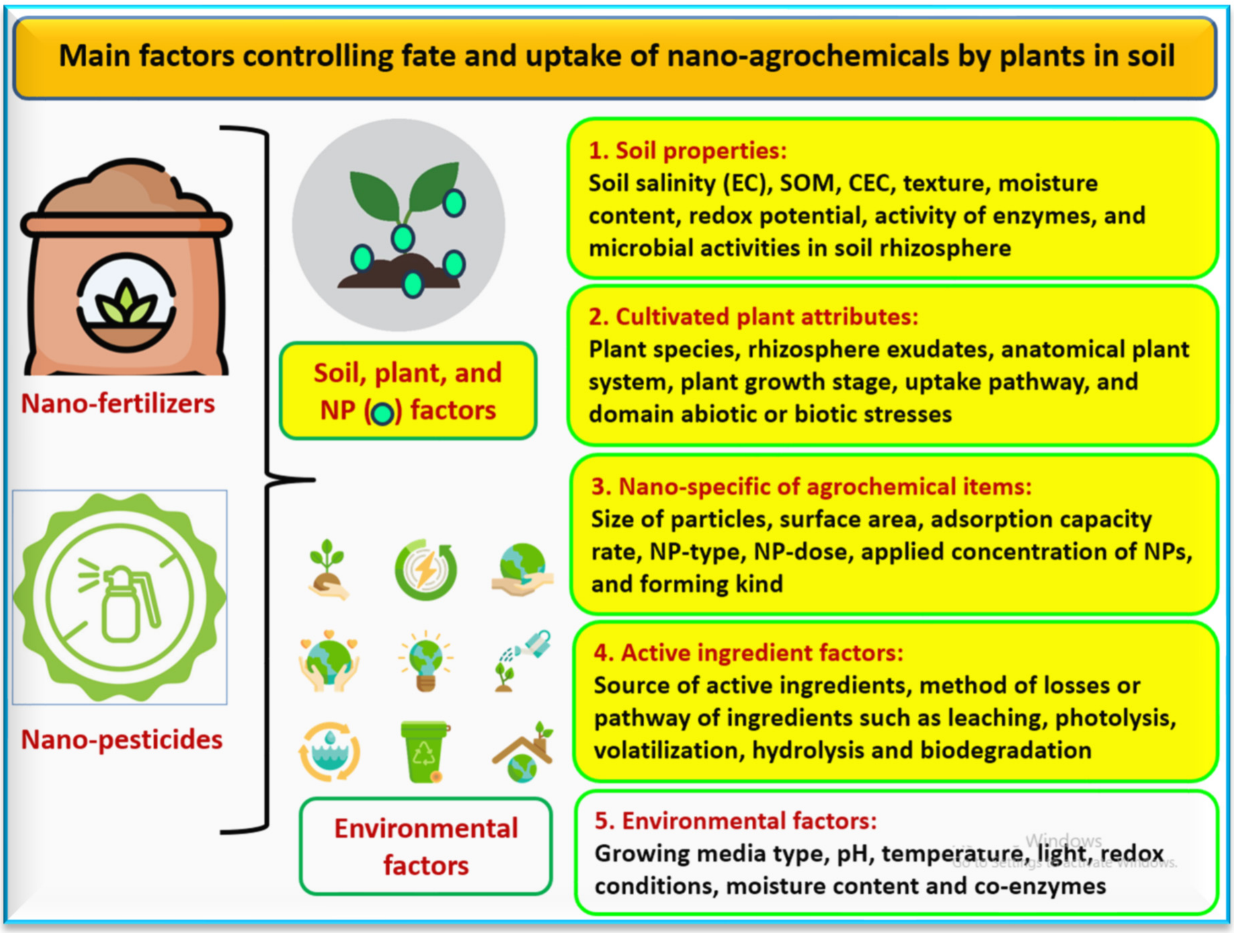

Figure 5. There are different suggested factors affecting the fate of nano-agrochemicals in soils and their uptake by cultivated plants, which include soil, plants, nanoparticles (NPs), and environmental factors. SOM, soil organic matter; CEC, cation exchange capacity. Sources: from different refs., referring to the text).

Are nanopesticides really necessary for producing cleaner agro-products? The main target of using nanopesticides is to avoid the harmful impacts of conventional pesticides on the environment (mainly environmental pollution, soil degradation, and pesticide resistance), due to overdose, inefficient usage, and post-application losses [79,81,82]. Properties of pesticides in nano-formulations could improve their efficiency by enhancing solubility, permeability, and stability, as well as their protection from premature degradation and controlling their release profile. Nano-pesticides may involve nano-encapsulations (lipid-based, polymeric, silica-, and clay-based), nanomaterials as active ingredients, nano-emulsions, metal-organic framework-based nano-formulations, greener nano-formulations, and nano-suspensions [81]. Seeking sustainable agriculture, nano-formulations of pesticides have recently been developed to modulate the plant-associated microbiome [76,77]. Nanotechnology strategies can decrease the harmful effects of pesticides on the agroecosystem via their nano-specific properties, which may include large surface area, small size, and ease of modification for developing sustainable agriculture [79].

Concerning nanofertilizers, there is no increase in agro-productivity under stress and climate change without enough/suitable amounts of agrochemicals (primarily chemical fertilizers and pesticides). Nanopesticides and nanofertilizers as nano-agrochemicals are considered controlled-release nanomaterials, which mainly depend on properties of the environment besides soil, plants, and NMs such as temperature, pH change, redox conditions, light, and the presence of enzymes, as presented in Figure 5 [23]. Why are nanofertilizers a promising approach for sustainable agricultural production? Nanofertilizers are considered eco-friendly alternatives to chemical fertilizers, which have several environmental problems, especially under excessive application. Many problems for the food chain can be expected due to the intensive use of chemical fertilizers because of their drastic deteriorating effect on agroecosystem health, degradation of soil fertility, and damage to human health [83]. Nano-enabled fertilizers are agrochemicals that have the ability to control nutrient release, enhance nutrient use efficiency (NUE), economic feasibility, and environmental compatibility [84]. Many types of nano-structured materials are nutrient nanocarriers, such as nano-clays, carbon-based nanomaterials, hydroxyapatite NPs, mesoporous silica, polymeric NPs, and other nanomaterials [84,85]. However, nano-enabled biogenic fertilizers have been addressed to solve these challenges through the integration of biotechnological and nanotechnological approaches, which have revolutionized the food production and agriculture sectors [83]. The benefits of nanofertilizers were proven, especially under abiotic stress, by mitigating the adverse effects of soil salinity stress [86]. The main mechanism of this mitigation may involve decreasing the uptake of Na^+ by roots and their accumulation in the shoots, the Na^+/K^+ ratio, and increasing the K^+ uptake. NPs can improve plant salt tolerance by elevating the expression of Na^+/H^+ anti-port and tonoplast H^+-ATPase at the root membranes and shortening the root apoplast barrier, thus limiting Na^+ translocation to tissues of the shoot and reducing Na^+ toxic effects [87]. The mode of action of applied nanofertilizers mainly depends on the soil, plant, and environmental factors in addition to the characteristics of nanoparticles (Table 1).

Table 1. Impact of applied nano-based fertilizers on mitigating salinity stress.

Plant Species	Applied Nanofertilizer and Its Dose	Salinity Stress	Experimental Conditions	Main Findings and Studied Growth Stage	Refs.
Williams banana (*Musa* spp.)	Green nano-silica from maize wastes (150 and 300 mg L^{-1})	Saline water EC: 4.12 dS m^{-1}	Field, sandy soil, and hot dry climate	Improved both productivity and quality of fruits by increasing antioxidant and osmo-regulators proline and soluble carbohydrates	[88]
Mustard (*Brassica campestris* L.)	Green Se-NPs from *Allamanda cathartica* L. flowers (12.5, 25 and 50 mg L^{-1})	NaCl (200 mM)	Seeds germinated in Petri plates for 4 days	Applied 25 mg L^{-1} Se-NPs improved germination by 31% and total chlorophyll content by 49% as a potential antimicrobial agent	[89]
Maize (*Zea mays* L.)	Chemical ZnO-NPs (50 and 100 mg L^{-1})	Salt stressed (50 and 100 mM NaCl)	Sandy loam soil (pH 7.85), (EC 1.52 dS m^{-1}), for 7 days	Nano-priming maize seeds (100 ppm) sown in trays improved metabolic and homeostasis under salt stress	[90]
Lemon verbena (*Lippia citriodora* Kunth)	Chemical nano-selenium (10 µM Nano-Se)	Levels of 40, 80, 120, and 160 mM NaCl	Plastic pot (4 L) filled with equal mixture of perlite and coco-peat for 60 days	Foliar nano-Se improved plant tolerance by increasing proline, soluble sugar, and secondary metabolites and reducing Na accumulation in roots and shoots	[91]
Date palm tree (*Phoenix dactylifera* L.)	Chemical nano-Se (80 and 160 ppm)	Saline water 5, 10 and 20 dS m^{-1} NaCl	Field exp. of date palm trees (6 years)	Under 10 or 20 dS m^{-1}, Se-NPs mitigated salinity by reducing the detrimental impact on trees in the lipid region	[92]
Safron (*Crocus sativus* L.)	Nano silicon (1500 ppm), particle size was 11–13 nm	Saline water: 1.96 and 6.04 dS m^{-1}	Field exp. clay loam, (pH 8.02 and EC 3.73 dS m^{-1})	Applied nano-Si and super-absorbent increased yield and chlorophyll; reduced leaf soluble sugars, proline, and lipid peroxidation	[93]
Dill (*Anethum graveolens* L.)	Foliar application of Nano-ZnO (3 mg L^{-1})	NaCl salinity (50, and 100 mM)	Soilless culture system in pots contain perlite	Applied nano-ZnO increased salinity up to 50 mM without remarkable loss in yield and growth characteristics	[94]

Table 1. *Cont.*

Plant Species	Applied Nanofertilizer and Its Dose	Salinity Stress	Experimental Conditions	Main Findings and Studied Growth Stage	Refs.
Wheat (*Triticum aestivum* L.)	Foliar Si-NPs (30, and 60 mg L^{-1})	Salt-water levels 35, 70, and 105 mM	Under green-house (silty soil texture)	Applied 60 ppm Si-NPs and bio-fertilizer inoculation increased yield under salt stress by promoting accumulated osmolytes and antioxidant enzymes	[95]
Strawberry (*Fragaria* x *ananassa* Duch.)	Si nanoparticles (2 mM), and sampling time (0, 24, and 48 h after treatment)	Salt stress (50 mM NaCl)	Pots contain a mixture of perlite and coco peat (1:1 *v*/*v*)	Nano-Si enhanced both enzymatic/non-enzymatic antioxidants and increased the transcription of salinity-related genes Si-application	[96]
Soybean (*Glycine max* L. var. 22 and 35)	Green TiO_2-NPs (30 and 50 ppm)	NaCl at 25, 50, 100, 150, 200 mM for 3 weeks	Seeds were germinated in box containing sterilized sawdust	Applied nanoparticles ameliorated oxidative stress, germination parameters, and vigor indices	[97]

Nanofertilizers have a tangible effect on the mitigation of salinity stress, depending on plant species, type of nanofertilizer, applied dose, and culture conditions. It is worth noting that green nanofertilizers are useful to mitigate soil salinity because they are sustainable and nearly non-toxic to cultivated plants and soil microbiomes. This form of nanofertilizer can improve both productivity and quality of banana fruits by increasing antioxidant and osmo-regulators proline and soluble carbohydrates under saline soils and a hot, dry climate mboxciteB62-agronomy-2649790,B88-agronomy-2649790. Furthermore, green TiO_2-NPs (50 ppm) ameliorated oxidative stress, germination parameters, and vigor indices of soybeans under salt stress up to 200 mM NaCl [71,97]. Depending on the investigation media and plant growth stage, green Se-NPs (up to 50 mg L^{-1}) improved the germination rate of mustard seeds by 31% and total chlorophyll content by 49% as a potential antimicrobial agent under salt stress at 200 mM NaCl in Petri plates for 4 days [63,89]. The next generation of nano-agrochemicals may include nanogels, nano-micelles, nanosuspensions, porous silica nano-emulsions, and nanoclays, which can promote seed germination by controlling the release of agrochemicals, bioavailability, solubility, and stability [72,98].

4.2. Nano-Soil Amendments

Why should we remediate saline soil? Soil salinization, or salinity, suffers from excessive accumulation of salts and degradation problems in soil (mainly decreased soil aeration, porosity, and water conductance due to the accumulation of Na^+ in the soil). The main features of soil salinity may involve high values of soil EC (salinization), pH (alkalinization), and exchangeable sodium percent (ESP; sodification), which result from the high solubility of Na-salts and precipitation of $CaCO_3$ under higher pH values [99]. The replacement of Na^+ on the exchange sites by Ca^{+2} is the general amendment of soil salinity by applying chemical amendments (especially gypsum, calcium sulfate, or $CaSO_4{\cdot}2H_2O$), organic amendments (biochar and chitosan), or nanomaterials (e.g., nano-gypsum, nano-sulfur, nano-biochar, and nano-chitosan). Applied nano-amendments and their mitigation of salinity stress under different conditions are tabulated in Table 2. Therefore, according to soil values of pH, EC (dS m^{-1}), sodium adsorption ratio (SAR), and ESP (%), there are four categories of salt-affected soils, including the previous parameters as follows: $\pm$4, $\pm$8.5, $\pm$15, and $\pm$13, respectively [100,101]. The main management strategies of soil salinity mitigation involve (1) removing excess salts from the soil profile by leaching and supplying enough water to prevent detrimental accumulated salts; (2) applying enough water for suitable methods of irrigation; (3) selecting the proper management of drainage and fertilization, as well as applying soil amendments like gypsum, sulfuric acid, elemental sulfur, or nanomaterials [102]. The suggested nano-managements have a crucial approach, which may depend on different mechanisms (Figure 6).

Table 2. Impact of applied nano-amendments on mitigation of salinity stress under different conditions.

Plant Species	Applied Nano-Amendments and Dose	Salinity Stress	Experimental Conditions	Main Findings	Refs.
Spinach (*Spinacia oleracea* L.)	Nano-gypsum at doses (120, 240, 480, and 960 kg ha^{-1})	Soil EC 25.55 dS m^{-1}	Pots contained clay saline-sodic soil (pH 8.87, ESP 56.42%, SAR 59)	Nano-gypsum is an alternative to traditional gypsum in mitigating salinity-sodicity effects	[103]
Not included	Nano-gypsum at doses 15, 30 and 45%	Saline soil (>4 dS m^{-1})	Investigated soil after applying nano-gypsum by 15, 30 and 45 days	Nano-gypsum improved soil health by reducing soil pH, EC, and SAR during field investigations	[99]
Periwinkle (*Catharanthus roseus* L. Don)	Chitosan nanoparticles (CSNP foliar at 1% concentration)	Salt stress (150 mM NaCl)	Plastic trays contained peat moss	CSNP ameliorated salt stress by activating antioxidants and inducing genes for higher alkaloid	[104]
Mung bean (*Vigna radiata* L.)	Nano-chitosan particles (400 ppm)	Salinity stress (4 and 8 dS m^{-1})	Seeds germinated in glass plates for 7 days	Nanochitosan is a cost-effective nanopriming for the management of salt stress in mung bean plants	[105]
Bitter melon (*Momordica charantia* L.).	Selenium-chitosan nanoparticles (Se-CS NPs)	Salt stress (50 and 100 mM NaCl)	Pots experiment under greenhouse conditions	Se-CS-NPs improved morpho-physiological, genetical, and yield under studied salt stress	[38]
Spearmint (*Mentha spicata* L.)	Chitosan-melatonin nanoparticles (CS-Mel-NPs)	Salt stress (100 mM NaCl)	Pots experiment under greenhouse conditions	CS-Mel-NPs is considered an innovative protective agent to mitigate salinity stress in the studied crop	[106]
Wheat (*Triticum aestivum* L.)	Biochar (5%) and Se-NPs (30 ppm)	3000 ppm saline water NaCl for 4 weeks	Pots (loamy soil, pH 6.43 and EC 0.6 dS m^{-1}) for 55-day-old plants	Biochar and Se-NPs protect leaf ROS damage, activate water transporter genes, and protect physiological traits from salt injury	[107]
Not included	Nano-biochar (10 nm) mixed with soil with 1% (*w/w*)	Saline soil (EC 8.68 dS m^{-1})	Sandy soil filled plexiglass columns, pH 8.3	Promoted forming soil water-stable macro-aggregates as amendments for saline-alkali soils	[108]
Wheat (*Triticum aestivum* L.)	Nano-biochar (10 nm) mixed with soil with 0.5, 1.0 and 2.0% (*w/w*)	Saline soil (5560 mg kg^{-1})	Growing container (soil pH = 8.3, SOM = 1.52%)	This biochar may improve soil aggregates and create a suitable environment for soil microorganisms	[109]
Maize (*Zea mays* L.)	Nanoparticles of silicon (NPs-Si, 75 mg kg^{-1})	Saline-sodic soil (EC = 6.50 dS m^{-1})	Pots filled with silty clay (pH 9.27, SAR 22%)	NPs-Si increased P and K availability in soil and reduced salt stress after maize harvesting	[110]
Not included	Nano-biochar (0.1, 0.2, and 0.5% as *w/w*)	Saline soils (1.47, 4.63, 10.12, 23.2, 58.5 dS m^{-1})	Batch adsorption experiments for adsorption P on different saline soils	A nanodose of 0.2% was a promising enhancer for P adsorption under salinity by precipitation on nano-form in salt-affected soils	[111]

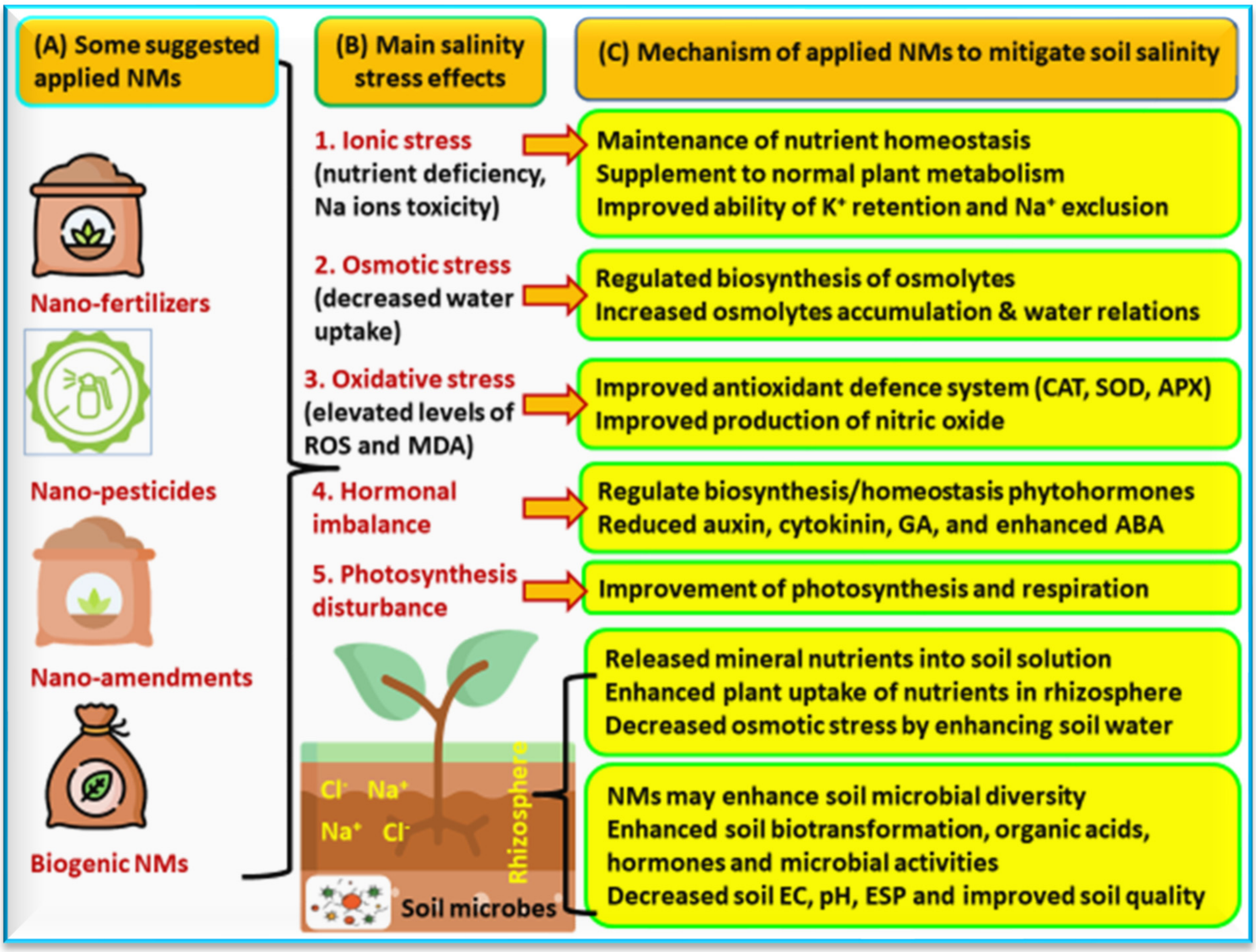

Figure 6. (**A**) List of some suggested nanomaterials (NMs); (**B**) the main effects of salinity stress; and (**C**) the assumed mechanisms by which cultivated plants under soil salinity can mitigate this stress after applying nanomaterials. Abbreviations: CAT, catalase; SOD, superoxide peroxidase; APX, ascorbate peroxidase; GA, gibberellic acid; MDA, malondialdehyde; ABA, abscisic acid. Sources: from different refs., referring to the text.

Nano-gypsum is considered one of the most important soil nano-amendments that can be applied for remediation of saline, alkaline, or saline-alkaline soils. This remediation may depend on many factors, such as soil characteristics, including mainly soil pH, EC, ESP, and the cultivated plant species or variety. In the presence of cultivated plants (spinach), nano-gypsum was a more effective alternative to traditional gypsum in mitigating salinity-sodicity effects (soil EC was 25.55 dS m^{-1}) when the applied dose was 240 kg ha^{-1} [103]. This effective action of nano-gypsum may differ when applied in the absence of cultivated plants, as reported under applying nano-gypsum at doses up to 45%, which improved soil health by reducing soil pH, EC, and SAR during field investigation [99]. Nanochitosan also has the ability to combat salinity stress in plants [112] as a sustainable agro-tool through its nano-formulation under abiotic stress [113]. Different nano-amendments have been proven to be effective for soil salinity mitigation, including inorganic forms such as nano-selenium, nano-silica, nano-gypsum, nano-hydroxyapatite, and organic amendments such as nano-compost, nanobiochar, and nano-chitosan [114,115].

Nano-biochar can be mixed with soil in the presence or absence of plants to amend saline soils [109]. Nano-biochar can be considered a sustainable solution for environmental remediation [116]. Nano-biochar has a potential impact on supporting cultivated plants under salinity stress through many suggested mechanisms. These mechanisms involve maintaining ROS homeostasis, improving the ability of K^+ retention and shoot Na^+ exclusion, promoting the production of nitric oxide, increasing the activity of alfa-amylase, decreasing lipoxygenase activity, and shortening the Na^+ root apoplastic to shoots [117,118].

4.3. Biogenic Nanomaterials

What is the difference between biofertilizers and nanofertilizers? In brief, bio-fertilizers are certain microbial species (e.g., *Azospirillum*, *Rhizobium*, *Cyanobacteria*, *Azolla*, and solubilizer microbes) that can promote the potential of nutrients during the soil biogeochemical cycles, whereas nanofertilizers are fertilizers containing nanonutrients for increasing crop productivity [119]. This difference is critical in the case of biofertilizers and biological nano-fertilizers, where the last one means how to produce nanofertilizers by using biological methods with microorganisms or plants. Several reports confirmed the sustainable potential of biological nanofertilizers compared with physical or chemical ones [83,85,120]. Several factors control the effectively applied nanofertilizers, which mainly involve the production methods of nanofertilizers (physical, chemical, and biological ones), the applied dose, the physio-chemical properties of NPs, the application method (soil, foliar, hydroponics, etc.), the cultivated plant species, the experimental conditions, and the salinity stress level. A survey on these previous factors to highlight the most effective factors on biological nanofertilizers under different kinds of environmental conditions and plant species was listed in Table 3.

Many studies have reported on plant growth regulators (PGRs) [15,121] and nanomaterials [13,122] for improving the productivity of crops under salinity stress. Under soil salinity stress, many studies reported the suggested mechanisms of PGRs by alleviating salinity stress in plants through enhancing accumulation of osmolytes in plant tissues (e.g., choline, glutamate, proline, glycine betaine, soluble sugars, and polyols), increasing antioxidant activities (e.g., ascorbate peroxidase, catalase, glutathione reductase, superoxide dismutase, monodehydroascorbate reductase, and peroxidase), and non-enzymatic antioxidants such as ascorbate, carotenoids, glutathione, polyphenols, and tocopherols [123,124].

Table 3. Impact of applied biological nanomaterials as bio-nanofertilizers on mitigating salinity stress under different conditions.

Plant Species	Applied Bio-Nano-Fertilizer and Its Dose	Salinity Stress	Experimental Conditions	Main Findings and Studied Growth Stage	Refs.
Rapeseed (*Brassica napus* L.)	Biological Se-NPs from 50, 100 to 150 µmol L^{-1}	Salt stress at 150 and 200 mM	Nano- or hydro-primed seeds in germination boxes	Biological Se-NPs (150 ppm) improved seedling growth and physiochemical attributes under stress conditions	[125]
Cucumber (*Cucumis sativus* L.)	Biological nano-selenium (nano-Se, 25 mg L^{-1})	Salt-affected soil (EC 4.49 dS m^{-1})	Field exp. at soil (pH 8.66) during summer	Nano-Se increased K^+ in leaves, regulated osmotic balance, and controlled opening stomata	[126]
Rice (*Oryza sativa* L.)	Foliar application of Se-NPs (6.25 mg L^{-1})	Saline soil (7.2 dS m^{-1})	Field exp. clay soil (pH 8.20)	Nano-Se mitigated salinity stress, improved growth, and increased grain yield	[127]
Broad beans (*Vicia faba* L. cv. Nubaria, 1)	Biological ZnO-NPs (50 and 100 mg L^{-1})	Saline irrigation water (150 mM)	Pot (loamy soil pH 7.8; EC 0.4 dS m^{-1})	Applied 50 ppm ZnO-NPs induced plant growth and accumulated antioxidants, secondary metabolites, and osmolytes	[128]
Wheat (*Triticum aestivum* L.)	Biological nano-Se doses (50, 75, and 100 mg L^{-1})	Salt stress (50, 100, and 150 mM NaCl) for 10 days	Seeds were germinated in petri dishes in dark incubator 25 °C	Applied 100 ppm nano-Se improved germination (%), vigor index, and germination rate index under 150 mM	[74]
Tomato (*Solanum lycopersicum* L.)	Bio-nano Se (100 mg L^{-1}) and Bio-nano-CuO (100 mg L^{-1})	Saline irrigation water (0.413, 1.44, and 2.84 dS m^{-1})	Seedlings were cultivated in pots contained a clay soil and sand (1:3)	Combined Bionano-Se and nano-CuO (50 ppm from each one) promoted tomato production under saline water irrigation	[22]
Common bean (*Phaseolus vulgaris* L.)	Bio-Si-NPs (2.5–5.0 mM L^{-1})	Contaminated saline soil (EC = 7.8 dS m^{-1})	Production of pods in polluted soil (18.4, 257, 253 ppm Cd, Pb, and Ni, resp.)	Applied 5 mM L^{-1} nano-Si was recommended for producing pods with reduced heavy metal content in such saline soils	[73]

Are biogenic nanomaterials important for sustainable agriculture? Why are these kinds of nanomaterials promising, especially under stressful conditions? It is well stated that bio-nanomaterials are an eco-friendly and economical alternative to soluble traditional agrochemicals due to their many benefits. These benefits may involve the low toxicity rate in the agroecosystem and the slow release of nutrients over the growing stage of the plant, which guarantee the continuous supply of nutrients (from bio-nanofertilizers) for higher crop quality and productivity while reducing many environmental risks [83]. These biological nano-agrochemicals will also not only promote crop production but will also contribute to food security, crop nutritional health, and environmental quality. The biological methods of nanomaterials include green and microbial methods (Figure 7).

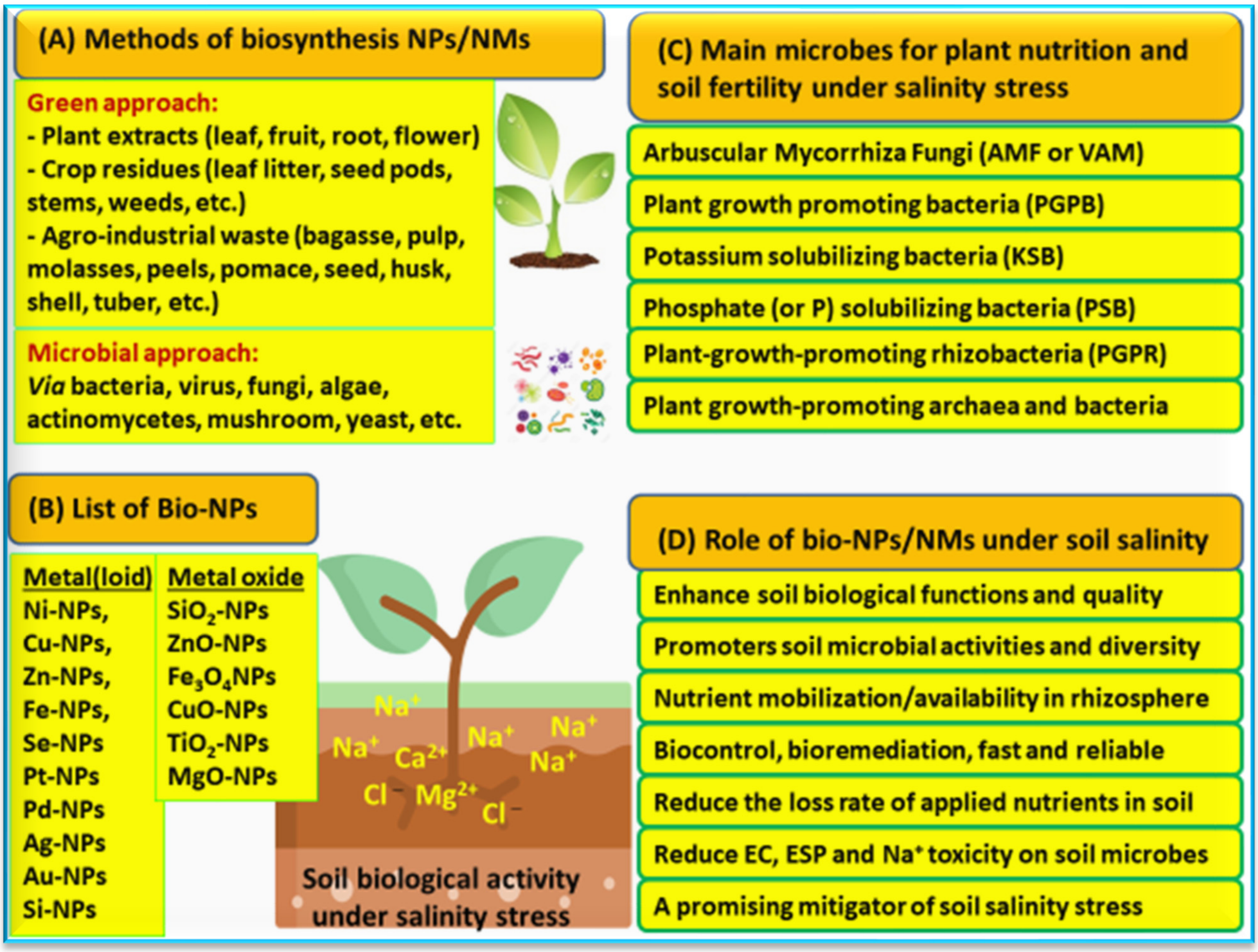

Figure 7. (**A**) Main biosynthesis methods of nanoparticles (NPs) or nanomaterials (NMs); (**B**) a list of the common biological NPs; (**C**) main microbes for improving soil fertility and pant nutrition under soil salinity; and (**D**) NMs on soil biological activities. Sources: from different refs., referring to the text.

There is an urgent need for innovative approaches for applying nanobiotechnology in the development of nano-biofertilizers or biological nanofertilizers. These fertilizers can be produced by containing both nanonutrients and plant growth-promoting microbes (PGPM) (e.g., *Bacillus subtilis* and *Pseudomonas fuorescens*) by nanoencapsulation [129]. Nano-biofertilizers can also be produced through the encapsulation of beneficial microbes within some nanometals like gold and silver, which strongly promote the productivity of different agricultural crops [83]. Several recent studies have reported on biogenic nanomaterials, in particular biological nano-fertilizers, such as PGPM-derived nano-fertilizers and their benefits and risks to soil health [129], biologically derived smart nano-structures for more efficient biosensors [130], biostimulants, and biogenic nanoparticles, which can be produced from agro-industrial waste and plant extracts [131]. More and more reports were published on the biological role of bio-nanofertilizers for more sustainable agriculture [132], for agri-business and environmental management [83], and as bio-emerging strategies for sustainability [34].

4.4. Nanocomposites

What are nanocomposites? Why are these composites vital as agrochemicals for crop production and environmental production? Nanocomposites are special materials formed from different materials to enhance their final properties, including mechanical, thermal, optical, biodegradability, and barrier properties. Nanocomposites are promising promoters for sustainable and eco-friendly cultivation, reducing the burden of mineral fertilizers and pesticides [133]. Nanocomposites have several benefits in the agriculture, food, and medicinal sectors. In agriculture, several nanocomposites have been developed for nutrient management [134], soil and water remediation [135], food packaging [136], environmental protection [137], and supporting plants under salinity stress [138]. The mode of action of nanocomposites mainly depends on the kinds of nanocomposites, their active components, their applied dose, and the environmental conditions. Several studies were reported on different types of nanocomposites, such as curcumin-polyvinyl alcohol nanocomposites [139], biochar nanocomposites [140,141], casein-coated iron oxide NPs [134], and chitosan nanocomposites [142,143]. The role of nanocomposites in the mitigation of salinity stress is presented in Table 4.

Table 4. The role of some applied nanocomposites under salinity stress and its mitigation.

Plant Species	Applied Nanocomposite Dose	Salinity Stress	Experimental Conditions	Suggested Impacts	Refs.
Sun flower (*Helianthus annuus* L.).	Curcumin with polyvinyl alcohol nanocomposite (20–60 mg L^{-1})	3000 ppm	Pots (sandy soil, pH 7.8, EC 0.74 dS m^{-1})	Foliar 20 mg L^{-1} was the optimum dose when using saline irrigation water	[139]
Wheat (*Triticum aestivum* L.)	Fe–Mn nanocomposite doped graphene quantum dots (200 and 500 mg L^{-1})	50 mM NaCl solution	Plastic trays with nutrient-free sand	Foliar 200 ppm of applied nanocomposite was effective for biofortification as a slow, controlled release	[138]
Dill (*Anethum graveolens* L.)	Biochar nanocomposite of Fe or/and Zn (30 g kg^{-1})	Saline solutions (1.6, 6, 12 dS m^{-1})	Pots (silty loam soil, pH 6.6, EC 1.6 dS m^{-1})	Nano-composite alleviated salt toxicity and improved root and shoot growth by decreasing Na-uptake	[141]
Dill (*Anethum graveolens* L.)	Biochar based nutritional nanocomposite of Fe or/and Zn (30 g kg^{-1})	Saline solutions (6, 12 dS m^{-1})	Pots (silty loam soil, pH 6.6, EC 1.6 dS m^{-1})	Nano-composite alleviated salt stress by reducing Na, increasing K, Ca, and Mg sugar uptake, and promoting hormones	[144]
Spearmint (*Mentha spicata* L.)	Salicylic acid and cerium oxide nanocomposite (50 mg L^{-1} and 100 µM)	25, 50 and 100 mM	Pots under greenhouse conditions	Nano-composite improves protein, antioxidants, phenolics, flavonoids, and essential oil content	[145]

Table 4. *Cont.*

Plant Species	Applied Nanocomposite Dose	Salinity Stress	Experimental Conditions	Suggested Impacts	Refs.
Safflower (*Carthamus tinctorius* L.)	Biochar-based nanocomposite of MgO and MnO (25 g kg^{-1} soil)	1.32, 6 and 12 dS m^{-1}	Pot experiment (silty loam soil pH 6.9, EC 1.32 dS m^{-1})	Nano-composites decreased salt toxicity by lowering SAR, ESP, and Na uptake by plants and osmotic stress under salinity conditions	[140]
Grape (*Vitis vinifera* L.)	Chitosan/salicylic acid nanocomposites at levels of 0.1 and 0.5 mM	50, and 100 mM NaCl	Pots (loamy sand soil, pH 7.50; EC 1.96 dS m^{-1})	Foliar nanocomposite at 0.5 mM was a biostimulant for improving grape yield under salinity stress conditions	[146]
Safflower (*Carthamus tinctorius* L.)	Biochar-based nanocomposite of MgO and MnO (25 g kg^{-1} soil)	6 and 12 dS m^{-1}	Pot experiment (silty loam soil pH 6.9, EC 1.32 dS m^{-1})	Nano-composites decreased Na-toxicity and productivity by improving the phenological and morphological parameters of plants under salinity stress	[147]
Wheat (*Triticum aestivum* L.)	Nano-chitosan-encapsulated nano-silicon particles	Salt stress 100 mM	Pots (2 L) filled with equal amounts of perlite and soil	Nano-composite improved the enzymatic and non-enzymatic antioxidants and reduced photodamage of chlorophyll and proteins	[142]
Wheat (*Triticum aestivum* L.)	Chitosan-proline nanoparticles (100 mM for 18 h)	Saline (120 mM NaCl) conditions	Pots filled with acid-washed sand (2.5 kg) in glasshouse	Co-applied nano-priming and biochar improved salt tolerance through the activation of antioxidants and the continuation of C-assimilation	[143]

Treatments with nanocomposites of chitosan or biochar are common under salinity stress and are applied at low doses, which are able to mitigate osmotic stress under the cultivation of different crops, such as dill [141], safflower [140], grape [146], and wheat [142,143]. Nano-chitosan can support previous crops due to being non-toxic, having greater adsorption ability, having a higher surface area, and having a higher ability to encapsulate with other active molecules with high encapsulation efficiency compared to the control [148]. These results were confirmed under pot conditions and under different controlled saline soils (Table 4). There are many advantages to biological nanocomposites, such as biodegradability as eco-friendly biopolymers, improved characteristics, and a lower carbon footprint due to lower emissions of greenhouse gases [149]. Biopolymer-based nanocomposites are effective candidates for controlling and slowing the release of different agrochemical formulations due to their features. They may involve high-effective carriers of core ingredients precisely to the plants, lowering environmental pollution risks, and apply agrochemical amounts due to less frequent applications. They are also safe to use, reduce environmental impacts, enhance water retention properties, and are designed to target specific sites of weeds or pests [149].

4.5. In Vitro Nano-Management

The study of applied nanomaterials under saline conditions can be performed even under in vitro conditions. Nano-plant tissue culture means the study of certain plant species grown on sterile nutrient medium supplemented with nanoparticles under fully controlled conditions. This kind of study is crucial nano-management for many in vitro plant biology studies, such as embryogenesis, cytology, pathology, morphogenesis, and clonal propagation [66]. The successful growth and development of in vitro plants depends on factors related to the type of explants, the genotype, the culture medium, methods of surface disinfection, the intensity of light, temperature regimes, and growth regulators. There is a positive impact of applied nanoparticles on plant tissue culture; for example, they can improve the germination of seeds, enhance plant growth, stimulate the production of bioactive compounds, and protect plants under salinity stress (Table 5).

Table 5. Impact of nanomaterials on enhancing salt tolerance under in vitro conditions.

Plant Species	Applied Nano-Particle and Its Dose	Salinity Stress	Main Findings and Studied Growth Stage	Refs.
Coriander (*Coriandrum sativum* L.)	Proline doped ZnO nanocomposites (50 and 100 mg L^{-1})	50 mM NaCl	ZnO-proline-NPs mitigated the adverse effects of salt stress by reducing oxidative stress and improving biomass at 100 mg L^{-1}	[150]
Coriander (*Coriandrum sativum* L.)	ZnO- glycine betaine nano-composite (100 mg L^{-1})	50 mM NaCl	Reduced oxidative and osmotic stress as detrimental effects of salinity conditions; increased plant length and biomass	[151]
Tomato (*Solanum lycopersicon* L.)	Nanoparticles of Fe_3O_4 (3 mg L^{-1}), ZnO (30 mg L^{-1})	25, 50, 75 and 100 mM NaCl	Applied NPs increased callus induction and regeneration by reducing the stress of osmotic conditions; callus induction was noticed with Fe_3O_4-NPs, while regeneration was observed with ZnO-NPs	[122]
Grapes (*Vitis vinifera* L.)	Iron nanoparticles at 0.08, and 0.8 ppm, and potassium silicate 0, 1, 2 mM	0, 50, and 100 mM NaCl	Iron-NPs at 0.8 ppm and 2 mM K-silicate increased total protein content and decreased proline and enzyme antioxidants. Cuttings can be produced efficiently using tissue culture-based techniques	[152]
Strawberry (*Fragaria* × *ananassa* Duch.)	Iron-NPs at 0.08, and 0.8 ppm and salicylic acid (SA) at 0.01, 0.05 mM	50, and 100 mM NaCl	Both SA and iron-NPs improved all growth-related parameters and increased the content of pigments. Producing transplants using tissue culture with Fe-NPs at 0.8 ppm and 0.05 mM SA	[153]
Garden cress (*Lepidium sativum* L.)	Nanographene oxides (NGO; 150, 300, and 450 mg L^{-1})	NaCl (1.5% *w*/*v* NaCl)	NGO at 150 and 300 ppm can alleviate salinity-negative impacts in callus cultures by increasing in vitro phenolic biosynthesis	[154]
Banana (*Musa acuminata* 'Grand Nain')	Nano-SiO_2 (50, 100, 150 mg L^{-1})	50 mM NaCl	Enhanced shoot growth and chlorophyll content	[111]
Strawberry (*Fragaria* × *ananassa* Duch.)	Iron nanoparticles at 0.08, and 0.8 ppm and SA at 0.01, and 0.05 mM	0, 50, and 100 mM NaCl	SA at 0.05 mM and 0.8 ppm Fe-NPs alleviated the adverse impacts of salt stress by increasing proline, superoxide dismutase, and peroxidase enzymes	[155]

At different salinity levels, many kinds of nanoparticles were used in vitro for improving plant growth under such stress, including metal NPs or nanocomposites (Table 5). Plant tissue culture is considered an economically applicable technique for producing grape softwood cuttings [152] or strawberry explants/transplants [153] or mitigating salt stress on plants such as coriander [150], banana [111], and tomato [122]. The applied nanomaterials included a variety of nanoforms, such as metal/metalloid NPs or nanocomposites. Different types of nanocomposites were investigated in vitro under salinity stress, such as proline-doped ZnO nanocomposites [150] and ZnO-glycine betaine nanocomposites [151].

5. Nano-Management under Toxicity Conditions

Despite the previous potential benefits of nanomaterials, many reports pointed out the expected harmful effects of intensive applications of such NMs in agroecosystem compartments as nanotoxicity [156–158]. These compartments may involve the nanotoxicity of the soil rhizosphere, aquatic life, cultivated plants, soil organisms, farm animals, groundwater, drinking water, the food chain, and humans. However, there are still significant gaps in research and a lack of rigorous monitoring of this nanotoxicity [130]. This toxicity has many levels that are needed to be investigated, such as phytotoxicity, cytotoxicity, and genotoxicity (Figure 8). Higher doses of NMs may cause cytotoxicity and genotoxicity for living organisms (plants and microbes) through damage to DNA structure, a reduction in the viability of cells, an alteration in genes, aberrations in chromosomes, and a reduction in the mitotic index [159]. The phytotoxicity study of engineered NPs is an emerging concern to elucidate their potential effects on plant systems [160]. This phytotoxicity is known to be totally controlled by the chemical nature of the element (NP), surface charge, size, coating molecules, and environmental factors like pH and light [157]. The toxic level of applied nanomaterials or nanoparticles on cultivated plants was reported. This toxic level mainly depends on the plant species, applied dose and type of NPs, size of applied NPs, cultivation method or growing medium, method of application, etc. It was found that applying nano-zero-valent iron (nZVI) caused toxicity to mung bean under hydroponically cultured seedlings at 600 mg L^{-1} [161], whereas applying more than 200 mg L^{-1} nZVI to *Herbaceous cattail* exhibited strong toxic effects [162]. Depending on the type of NPs and plant species, it was noticed that the toxic level of Fe-based NPs may range from 50 to 2000 mg L^{-1} [163].

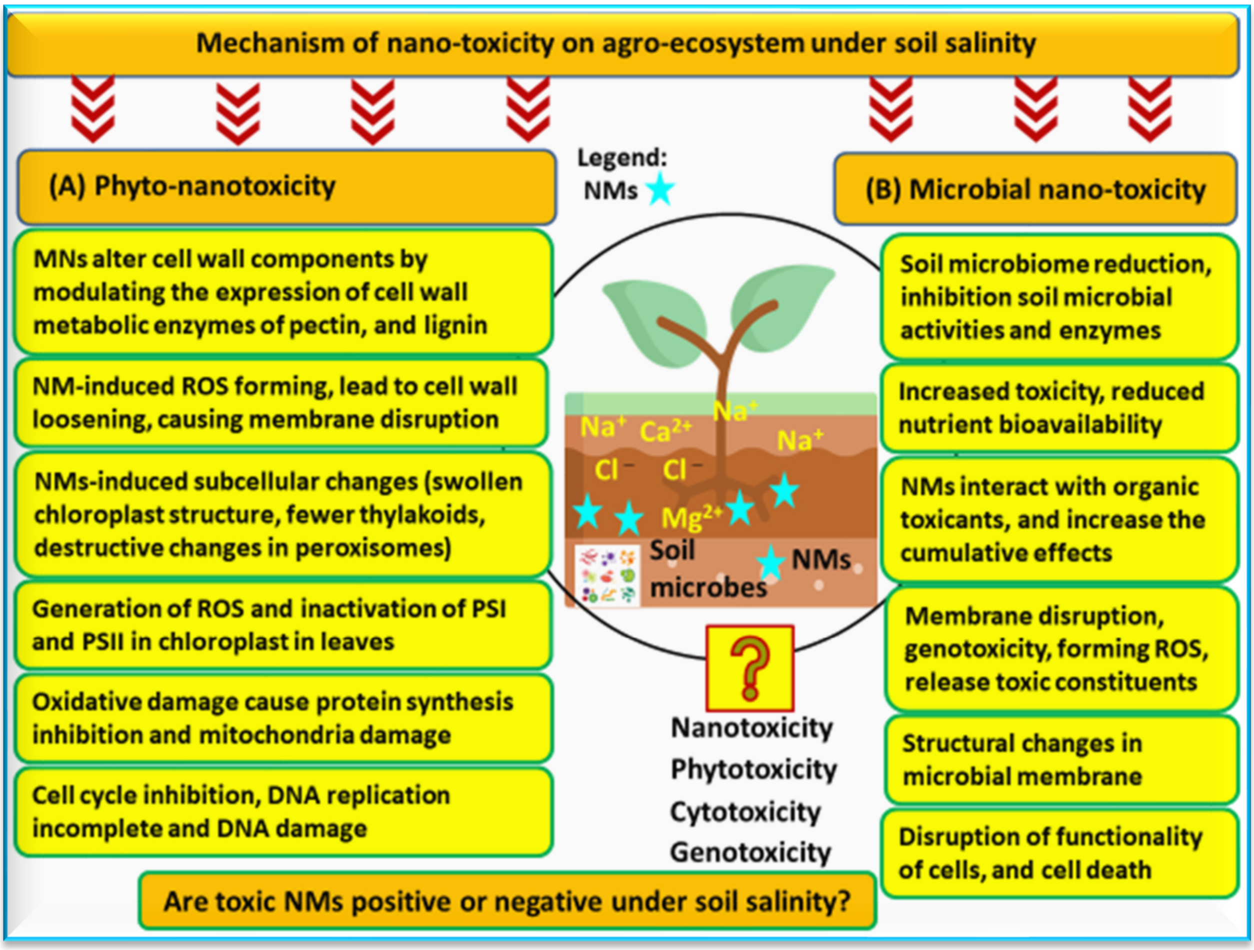

Figure 8. The possible mechanisms of nanotoxicity on cultivated plants and soil microbes are phytotoxicity and microbial nanotoxicity. Abbreviations: ROS, reactive oxygen species; PSI, PSII, Photosystem I and II. Sources: from different refs., referring to the text.

Concerning the nanotoxicity on soil microbiomes, NMs have direct impacts due to their high applied dose, which reduces nutrient bioavailability. The mechanism of this action may be microbial cell membrane absorption, leading to direct association with amino, carboxyl, and thiol functional groups of proteins and nucleic acids. Regarding the indirect impacts of nanotoxicity, they can be attributed to the interaction with organic toxicants after they reach cumulative effects [164]. The possible mechanisms for direct nanotoxicity may include the disruption of membranes, genotoxicity, forming ROS, and release of toxic constituents, as well as structural changes in the microbial membrane, disruption of the functionality of cells, and eventually the death of cells [164]. Phytotoxicity is also an expected problem after applying intensive amounts of manufactured NMs [1]. Many reports confirmed the problem of phytotoxicity in agroecosystems [156,163]. These studies have reported that excess metal-based NPs cause oxidative stress on cultivated plants through the generation of ROS, reducing plant growth, causing hormonal imbalance, and causing damage to the secondary metabolism, along with potentially genotoxic consequences [156]. The main problem with nanotoxicity effects on environmental components is the lack of methodology to monitor and follow accurately the NPs fate in soil and different biological systems, besides the insufficient knowledge regarding reliable results [163].

Under soil salinity stress, the current situation is very complicated due to the interactions among many factors, including the toxicity of soil salinity, phytotoxicity, soil microbial toxicity, and nanotoxicity. What is the contribution of each component in this toxicity state? What is the real situation of salinity toxicity on both cultivated plants and soil microbes in the presence of toxic and non-toxic NMs (in cases of higher and optimum doses)? Are higher applied NM doses antagonistic or synergistic to the toxicity of soil salinity? Which regulatory ecotoxicity tests and protocols should be used in research? On the other hand, several studies have been published on the role of applied NMs or NPs for enhancing cultivated plants under soil salinity conditions, but very few or no studies, as far as we know, have focused on the interaction between the toxicity of soil salinity and the toxicity of applied NMs and their impacts on soil microbes and cultivated plants. Depending on the applied dose of NPs, they can enhance the salinity toxicity tolerance in some plant species by modulating the photosynthetic efficiency, antioxidative enzymes, and cellular damage [87,165].

6. Future Perspectives

The utilization of nanomaterials for improving crop production is expected to transform future agricultural practices. Although nanotechnology has crucial solutions for improving crop productivity under stress, such as soil salinity, there are unforeseen consequences to applying NMs. The ecotoxicological consequences of NMs exposure can be linked to the food chain, which threatens both global food safety and the entire environment due to their detrimental impacts in various walks of life, i.e., farms, households, and industry. Hence, there are many limitations that should be considered before the extended use of NMs under normal and stress conditions, such as comprehensive analyses of NMs to assess their implications for human health [166,167], the focus on sustainable production of nano-agrochemicals for multiple farming practices [78]), the multiple-facet role of applied NPs in combating stress, their phytotoxicity, and their anti-microbial activity [168], activating the role of the agri-extension sector in increasing the awareness of farmers and others towards the hazards of nanotoxicity [34,169]), etc. More studies are urgently needed on possible interactions between toxic NMs (when they are applied at higher doses and/or after their accumulation in the agroecosystem) and soil salinity toxicity. It is necessary to clarify whether these interactions have synergistic or antagonistic effects, especially on soil microbes and cultivated plants. Are toxic NMs positive or negative for soil salinity? Moreover, the probable strategies that may be adopted for the suppression of nano-phytotoxicity are needed to ensure the safe and nano-sustainable application of these strategies for crop productivity, especially under salinity stress.

7. Conclusions

Agriculture is a crucial sector that derives our lives from needs and necessities. Several agro-practices face serious, problematic stress, which represents mainly mismanagement. Therefore, it is very useful to monitor and maintain these agro-practices at different levels, including local, national, and global ones. Crucial studies are needed, including those that compile both field and in vitro applications together. Soil salinization, a common problem due to climate change, is proposed to increase in arid and semiarid regions, especially in irrigated lands. Global soil salinity is a real and dangerous threat to global food security, which has three major threats of toxicity, including ionic, osmotic, and oxidative stresses. On the other hand, nanotechnology is proposed as a promising approach for supporting our lives when we encounter problems every day, like soil salinity. In the current study, a large number of studies investigating the relationship between nanotechnological applications and salt tolerance in plants were reviewed. There are many suggested functions of nanomaterials used in nanomanagement, such as regulating the biosynthesis of osmolytes, increasing the accumulation of osmolytes and water relations, improving the antioxidant defense system, and producing nitric oxide, as well as improving photosynthesis and respiration. A nano-management approach for mitigating salinity stress is a vital strategy through many applied NMs such as soil nano-amendments, nano-agrochemicals, nanocomposites, derived smart nanostructures, etc. The intensive applications of NMs may lead to the establishment of a nanotoxicity problem, which needs more attention in nanomanagement, particularly under salinity conditions. This nanotoxicity has a strong link with all environmental compartments, including soil, water, and plants, leading to phytotoxicity, cytotoxicity, and genotoxicity. Due to the strong interaction between nanotoxicity and the food chain, which directly impacts human health, more different levels of investigation are needed. These studies should focus on nanotoxicity in soil, water, and plants for human health under different stresses, such as soil salinization.

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