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Review

Can Nanomaterials Improve the Soil Microbiome and Crop Productivity?

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Abstract: Global issues such as soil deterioration, pollution, and soil productivity loss induced by industrialization and intensive agriculture pose a serious danger to agricultural production and sustainability. Numerous technical breakthroughs have been applied to clean up soil or boost the output of damaged soils, but they have failed to restore or improve soil health to desired levels owing to expense, impossibility in a practical setting, or, to a lesser extent, high labor consumption. Recent nanotechnology advancements promise to improve soil quality indicators and crop yields while ensuring environmental sustainability. As previously discovered, the inclusion of nanomaterials (NMs) in soils could manipulate rhizospheric microbes or agriculturally important microbes and improve their functionality, facilitating the availability of nutrients to plants and improving root systems and crop growth in general, opening a new window for soil health improvement. A viewpoint on the difficulties and long-term outcomes of applying NMs to soils is provided, along with detailed statistics on how nanotechnology can improve soil health and crop productivity. Thus, evaluating nanotechnology may be valuable in gaining insights into the practical use of NMs for soil health enhancement.

Keywords: nanotechnology; food security; microbes; salinity; sustainable agriculture

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Citation: Rajput, V.D.; Kumari, A.; Upadhyay, S.K.; Minkina, T.; Mandzhieva, S.; Ranjan, A.; Sushkova, S.; Burachevskaya, M.; Rajput, P.; Konstantinova, E.; et al. Can Nanomaterials Improve the Soil Microbiome and Crop Productivity? *Agriculture* **2023**, *13*, 231. https://doi.org/10.3390/agriculture13020231

Academic Editor: Nguyen V. Hue

Received: 8 November 2022
Revised: 13 January 2023
Accepted: 16 January 2023
Published: 18 January 2023

1. Introduction

The chance of unfavorable agroclimatic conditions growing in the future will surely lead to an increase in biotic and abiotic stressors, which will have a significant influence on agricultural productivity and soil health [1,2]. Soil is a key living ecosystem that supports plants and animals and has a variety of activities that can help to alleviate or adapt to changing conditions. Fertile soils are essential for long-term food security [3]. Food security, however, remains a huge unresolved issue for many developing countries as a result of climate change and bad farming methods. At the moment, the agriculture industry faces substantial issues such as increasing soil productivity, improving fertility and enrichment, enabling crop adaptation and tolerance, and making efficient use of agrochemicals [4].

In this context, nanotechnology in agriculture has gained recognition in recent years [5]. In soil, nanomaterials (NMs) are reported to directly affect the functionality of soil microbes; as a result, they may promote plant growth by enhancing the physiochemical characteristics of the soil if the application procedure is optimized [6–8]. In a recent report, coated FeO NMs were applied for improving the effectiveness of bioremediation of Pb and Cd contaminated soil by *Halomonas* sp., and results showed 100% removal of Pb after 24 h and Cd after 48 h, as compared to removal by bacteria or only NMs [9]. In another study, dried *Staphylococcus aureus* and the n-Fe_3O_4-Phth-S complex were applied for the removal of Cu, Ni, and Pb from aqueous solutions. This combination acted as an efficient bio-sorbent for adsorptive removal and extraction of 99.4–100% for Pb(II), 92.6–97.5% Ni(II), and 83.0–89.5% for Cu(II) [10]. The application of heavy metal-resistant bacteria, i.e., *Bacillus cereus* (PMBL-3) and *Lysinibacillus macrolides* (PMBL-7), synergistically eliminated the Cr by 60%, the Cu by 70%, and the Pb by 85% with the application of ZnO NMs at 5 mg L^{-1}, as compared to *B. cereus* (80 and 60%) and *L. macroides* (55 and 50%) at neutral pH, respectively [11]. The removal of Cd (46.66%), Pb (48.88%), and Zn (47.01%) from polluted soil was enhanced by the input of OA-nZVI NMs at 0.4 g kg^{-1} [12]. The application of nZVI with biochar increased the immobilization of Cr in edible *Brassica napus* and *B. rapa* subsp. Pekinensis [13]. Nanobiochar and nano-water treatment residue have significantly enhanced the dehydrogenase (32.8%) and catalase (566.7%) activities compared to the control and greatly improved the growth of *B. napus* (increased yield by 150.64%) in the soil [14].

The use of nanotechnology also improved the delivery of nutrients and soil fertility by stimulating soil enzymes [15]. Plant growth and soil health can both be improved by the interplay of NMs with rhizospheric bacteria [8,16]. The utilization of industrial coated NMs-based products, such as nano-fertilizers [17], which showed a positive effect on the soil microbial community [18], changing rhizospheric microbiome characteristics, plant growth, yield, and yield quality, are just a few reasons for the prevalence of NMs in the rhizospheric region. A review, however, concluded that the introduction of NMs into the soil ecosystem affects the structure of the soil and activity in the rhizosphere [19,20]. The net impact of NMs on the soil microbiome was also described to vary depending on the characteristics and concentration of NMs, the kinds of inhabiting microbial species, and the soil conditions [21]. Thus, the use of NMs could have positive impacts on plants as well as soil microbes, but only when they are applied in a regulated manner in terms of application dose, exposure duration, types, and sizes of produced NMs [22].

Recently, manipulating soil microbes has attracted great attention from the scientific community to overcome adverse environmental stresses and factors for plant growth and sustain the soil. Soil microbes play a crucial role in plant growth, even under stress conditions reported in a large number of scientific publications [23–25]. Thus, the present review highlighted the nano-inventions to improve soil health via improving soil microbiota, future perspective and environmental fate are also discussed. A thorough literature search was performed using keywords such as nanomaterials, nanoparticles, soil health improvement, modern agricultural approaches, nanotechnology, zinc-based NPs, iron-based NPs/NMs, soil microbes, degraded soil, impacts of NPs on soil health and soil community, green technologies, biochar/nanobiochar, food security, and sustainable agriculture. A comprehensive search was conducted for available electronic information resources in the Scopus, Web of Science, and Science Direct databases, and the most appropriate research and review studies were considered.

2. Nanoparticles in Restoration of Soils

Soil, as a natural body, is an organic-carbon-mediated domain with liquid, solid, and gaseous phases that interact at various sizes and produce a plethora of ecosystem products and services. Soil organic carbon has been observed to have a significant effect on soil quality, functionality, and health. Carbon transformations, soil structure maintenance, and the nutrients cycle play a significant role to maintain soil health [26,27]. These factors are primarily dependent on the biochemical process and microbial activities. If this activity can be enhanced by NMs applications, it might result in improvements in soil fertility and health. Soil fertility and productivity are dependent on the interactions of microorganisms and soil animals since soil biodiversity is believed to be the primary factor determining soil health. The soils treated with graphene oxide and carbon nanotubes lowered the soil enzyme activity in the short term and had no significant impact on microbial biomass [28].

Due to intensive cultivation, soil biodiversity is being damaged at an alarming stage. With the new hope, one of the most important inventions of the twenty-first century, nanotechnology, has the capacity to expand current agricultural practices and enable sustainable development by enhancing management and conservation practices and reducing agricultural input wastes in a variety of environmental contexts [29]. Nanotechnology could enhance the activities of soil microbes and animals with a mixture of other agricultural practices and soil health-improving amendments. Enhancing soil health and restoring degraded soil will help formulate a more climate-resilient cultivation system. It will contribute to stable and high income from cultivation over a period of time in a sustainable way. The soil conditions in which plants are grown have major impacts on them. In this context, soil stress variables such as salt, dryness, acidity, suboptimal root zone temperature, nutrient availability, and adequate soil biota functionality are critical for crop output since they can impede plant performance [30,31]. The variations in soil microbiome achieved via nanotechnology will not only improve soil health but also enhance crop production. Plant growth that is induced under adverse soil conditions by root-associated microorganisms using NMs to induce nutrient cycling and phytostimulation is shown in Figure 1 in schematic form [32].

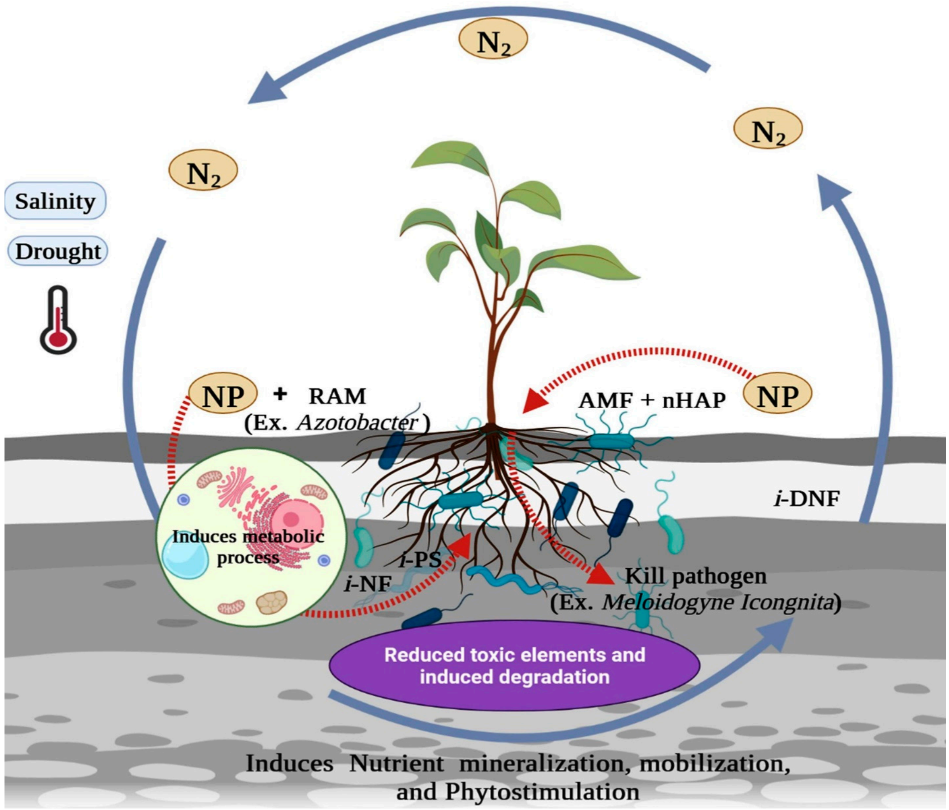

Figure 1. Plant growth is induced through nanotechnology under adverse soil conditions by enhancing root-associated microbe functionalities and improving nutrient cycling and the phytostimulation process. *i*-PS (Induced phosphate solubilization, *i*-NF (Induced Nitrification), *i*-DNF (Induced Denitrification), NP (Nanoparticles), RAM (Root Associated Microbes), AMF (Arabuscular Mycorrhiza), and nHAP (Hydroxyapatite Nanoparticle).

2.1. Manipulation in Soil Microbiome via Nanotechnology for Soil Health Improvements

The term "plant microbiome" refers to all the bacteria that live on various plant parts. These microorganisms include those that live on the aerial parts of plants, such as the leaves (phyllosphere), the outside of the roots (rhizoplane), in a small area of soil that is directly influenced by root secretions, i.e., the rhizosphere, and on the inside of the plants' system, i.e., the endosphere [33,34]. Types of plants, their age and health, secretions, environmental conditions, physicochemical properties, microbial abundance in soil, and other variables play an important role in the intricate interplay between the plant and its microbiome [35,36]. It is appealing to note that research has indicated that plants choose particular bacteria to colonize their rhizosphere [33,37]. Additionally, even in the existence of the same conditions, the microorganisms found in a plant's endosphere, phyllosphere, and rhizosphere may alter significantly. By releasing certain plant exudates, plants can even use particular microbial communities to carry out particular tasks [38]. Nutrient fixation, nutrient mobilization, sequestration of micronutrients, synthesis of effector molecules, tolerance, and defense mechanisms against plant diseases are only a few examples of the numerous conventionally recognized plant support services provided by bacteria [8,39,40].

In this climate-changing era, it is required to explore realizations into soil microbiome functionality and adaptation, and it can modulate for better performance or support to plants and soil health. The biogeochemical cycling of macro- and micronutrients as well as other essential elements for the growth of plants and the life of animals rests to a greater extent on soil microbiomes [41]. The manipulation of soil microbiome may cut down the huge input of pesticides by improving the potential of soils to fight or recover from infestation and diseases as well as generate suppressiveness naturally [42]. Microbes that supply nutrients to host plants include mycorrhizal fungi and rhizobia, a diazotrophic bacteria that develops root nodules in legumes [43]. Meanwhile, bacteria that mobilize nutrients, such as those that solubilize phosphate (such as *Pseudomonas* sp. and *Pantoea* sp.), can change phosphate into insoluble forms such as $Ca_3(PO_4)_2$ [44]. Similar to IAA, other chemicals produced by diverse microbes are known to aid in the growth of plants [45]. By producing organic acids or siderophores, bacteria can also provide micronutrients such as zinc to plants [8,35,46].

The NMs have unique surface properties that enable significant biological activities that are potentially useful for amending the physiochemical and biological characteristics of the soil. The surface of NMs can affect their hydrophobicity as well as the biochemical and soil environments, triggering nutrient mineralization and mobilization through numerous integrated mechanisms mediated by plant root exudates, soil organic matter, and rhizospheric bacteria [47,48]. Under hydroponic nutritional conditions, Cu-based NMs (10 mgL^{-1}) showed increased root exudation in *Cucumis sativus* and released Cu ions that are used by the plant [49]. Similarly, TiO_2 and Fe_3O_4 (50–200 mg kg^{-1}) NMs promoted plant root exudation by decreasing the pH and mobilizing nutrients in saline or alkaline soil, and CuO (500 mg kg^{-1}) NMs improved the soil pH in acidic soil [50]. These studies advocated for NMs as suitable agents for achieving soil pH neutrality, thereby increasing nutrient mobility and soil health. NMs can boost phytostimulation by enhancing phytohormone biosynthesis, varying gene expression, antioxidant activities, regulating nutrient transport, carbohydrate, fatty acid, and amino acid synthesis, and so on [50]. CuO and ZnO-based NMs induce phenols, anthocyanins, and phenols (antioxidant substances) in *Glycyrrhiza glabra* [51], whereas TiO_2NMs increase nutritional content such as P and Nin *Oryza sativa* [52].

Microbial diversity in the rhizospheric region demonstrates the natural interplay of root exudates and microbe-mediated quorum sensing mechanisms and adaptations [33], and these microbes are capable of producing a large number of bioactive secondary metabolites such as siderophores, lipopeptides, and exopolysaccharides, and nanomaterials influence the development of secondary metabolites by root-associated microbes [53]. Siderophores facilitate the chelation and dissolution of certain elements and mineral phases [54,55]. The dissolution of hematite (Fe_2O_3) NMs was reportedly sped up by the increased microbial siderophores synthesis; the released Fe was then further absorbed by the plants [56]. In another work, Avellan et al. [57] demonstrated that siderophore-mobilized Fe exhibited considerably lower toxicity when utilized to metabolize the Fe-doped, high aspect-ratio of NMs. Several metals can be chelated by siderophores, including Cu, Zn, and

Mn [58,59]. Siderophores may theoretically improve the dissolution of NMs and assist in heteroaggregation with soil minerals owing to their high affinity for metal chelation [60]. The link between the plant and soil microbiome is reported to be bidirectional, in which microorganisms acquire nutrients from the carbon-rich chemicals produced by the plants while the microorganisms help the plants in their growth and development [61]. It is appealing to note that the microbiome of *Arabidopsis thaliana* has been demonstrated to regulate the plant's biomass and blooming time [62]. A. thaliana's rhizospheric microbial communities were discovered to be crucial to the plant's defense against the illness in a different study [38]. The wild species of *Nicotiana attenuata* have also revealed that the microbial community plays a similar protective role against wilt disease [63].

Comprehensive studies of the microbiomes found in plants may promote sustainable agriculture by lowering the necessity for pesticides and chemical fertilizers while boosting crop nutrition and productivity [64]. Plants have included a range of microbiomes that can change in response to shifting environmental conditions; thus, it is essential to identify and assess the core microbiome that is peculiar to plants and relatively stable. These microbiomes can be customized for certain needs, including enhanced development, disease defense, and agricultural quality [65]. Such thorough and methodical research will aid in increasing the sustainability of agriculture and reducing its dependence on agrochemicals.

NMs are one of the most often employed substances that could end up in soil among the many inorganic contaminants [66]. The microbial ecology of the soil or the plant may be affected by NMs, which could then have a direct or indirect effect on plant growth. For instance, it has been observed that soil microbial populations are impacted by nanoscale TiO_2 and ZnO [67]. The population of bacteria that fix nitrogen and oxidize methane drastically decreased after treatment with NMs, whereas the population of bacteria that break down refractory organic pollutants, notable members of the Sphingomonadaceae family, greatly increased. Arbuscular mycorrhizal root colonization was found to be mostly unaffected by the effect of TiO_2, one of the abundant soil nanomaterials, on the wheat microbiome, despite the populations of a particular set of microorganisms changing [68]. Additionally, the alteration in the microbial community can be used as a sign that soil has been contaminated with TiO_2NMs. A different study that looked at the impacts of Ag NMs on soil microbial communities in great detail found that these NPs had a significant effect [69].

Populations of ammonia oxidizers and proteobacteria significantly decreased after the application of Ag NPs at 0.01 mgkg^{-1}, while the density of actinobacteria, acidobacteria, and bacteroidetes rapidly increased by Ag NPs at the same exposure level (at 0.01 mg kg^{-1}). Exposure to Ag NPs at 0.01–1.0 mg kg^{-1} reduced the number of nitrogen-fixers, soil microbial biomass, and activity of the leucine aminopeptidase [70].In soils treated with C60 fullerenes with an average diameter of 50 nm, a three- to four-fold decrease in the density of fast-growing bacteria was noted [71]. In another study, TiO_2 and amine-modified polystyrene nanospheres were added to the *Lactuca sativa* seedling's rhizosphere to reduce the number of rhizospheric bacteria, which in turn inhibited the plant's growth [72]. *A. thaliana's* life cycle was significantly shortened when the soils were watered with wastewater containing nanomaterials [73]. Cyanobacteria populations were increased, and a variety of unknown archaea were discovered. Additionally, carbon NMs changed the microbial population in the *Oryza sativa* rhizosphere and were hazardous to the environment [74]. In a study on *Solanum lycopersicum* plants, adding CNTs to the soil did not alter the microbial population [75].

Numerous studies have been conducted to date on the impacts of NMs on microorganisms that mediate the cycling of several important elements, such as carbon and nitrogen [76]. Acid phosphatase, glycosaminidase, -glucosidase, and arylsulfatase, which are important enzymes for nitrogen and carbon cycling, are less active in soil samples exposed to Ag NMs [77]. Zhao et al. (2020) found that denitrification was the microbiological process that was most responsive to CuO NMs [78]. Another study found that leguminous Glycine max crops were unable to fix nitrogen when nano-CeO_2 was found in high concentrations [79]. The frequency of nodulation of *Medicago truncatula* by *Sinorhizobium meliloti* was significantly decreased by the existence of NMs in the soil, such as silver, zinc, and Ti [80]. Silver has been extensively explored among other NMs because of its well-known antibacterial capabilities. For instance, one study found that AgNMs prevented the free-living nitrogen fixer *Azotobacter vinelandii* from growing [81].

NMs can bind to bacterial exopolysaccharides and endure steric repulsion, which effectively stabilizes the suspension of NMs [82,83]. In accordance with Xiao et al. [84], Se-based NMs actively engage with the exopolysaccharides' -OH groups to form new C-O-Se bonds, which enhance the stability of Se NMs and prevent them from aggregating. Additionally, the exopolysaccharides -Se NMs showed enhanced antioxidant properties against the superoxide anion radical ($O_2^{\bullet}$) and the 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) ABTS radical cation ($ABTS^{\bullet +}$), indicating a potential use for the exopolysaccharides-Se NMs as a nano-formulation for plant Se nutrition. Since the solubilization and homo-aggregation of NMs are simultaneously and variably influenced by a wide range of environmental conditions, such as pH, ionic strength, and organic matter, it is difficult to predict the outcomes in the agricultural field [85].

Understanding the interplay between plant growth-promoting rhizobacteria (PGPR) and NMs in the rhizosphere, however, may present a good chance to look into low-cost, environmentally safe nano-formulations for agricultural applications. In the last decade, PGPR has emerged as a promising choice for enhancing crop performance and improving soil health under challenging environmental conditions [86,87]. It helps to convert inaccessible soil minerals into plant-available forms, suppressing pathogen activity, priming plant immunity, and alleviating abiotic and biotic stresses [88,89]. Similarly, mycorrhiza and rhizobia symbioses play a crucial role in the cycling of soil nutrients, the mineralization of organic matter, the microbial community and plant structuring, and ecosystem performance and resilience [21].

2.2. Nanotechnology in Reducing Soil Stress for Plant Growth

The soil conditions in which crops are grown are widely accepted as being the most important factor for the plant. Thus, soil stresses such as salinity, drought, compaction, drought, acidity, suboptimal root zone temperature, availability of nutrients, soil types, and soil biota functionality can hinder plant performance subsequently. These stresses (biotic–abiotic) have a direct effect on cultivation; however, they can be managed in a sustainable way by using modern innovations, especially nanotechnological approaches and nano-enabled products [30,31].

A recent study showed that the application of corban-based NMs enhanced *Z. mays* growth by improving nutrient uptake and it also improved soil fertility by stimulating soil enzymes [15]. The metal-based NMs, such as Fe, Cu, Co, and ZnO, showed growth enhancement in *Glycine max* under drought stress conditions [90]. The high-temperature stress is reduced by Se-based NMs in the *Sorghum bicolor* [91]. A large number of microbes, such as *Brevibacterium frigoritolerans*, *Bacillus thuringiensis*, and *Bacillus velezensis*, have been reported to alleviate NaCl stress by providing necessary substances via root secretion [92]. The joint application of Si-Zn NMs and plant growth-promoting microbes reduces the salt impact on plant growth [93]. ZnO-based NMs and biofertilizers' co-application showed to protect *Carthamus tinctorius* against salinity stress by increasing antioxidant enzyme activity and lowering malondialdehyde and proline levels [29]. These are the few works summarized in this review that showed that nanotechnology could manage several types of soil stress which directly/indirectly affect plant growth and quality yield.

2.2.1. Salinity Stress

Salinity is a key abiotic stressor that prevents plants from growing and slows down their developmental processes. More than 800 Mha of areas are affected by salt stress worldwide, which puts agricultural production at risk and reduces output [35]. Typically, osmotic and ionic stress, which is mediated by salt stress, affects the fundamental metabolic processes of protein synthesis, glucose metabolism, and lipid metabolism. Unusual increases in Na^+ and Cl^- in plants exhibited oxidative stress caused by reactive oxygen species (ROS) production, as well as cytotoxicity and nutritional imbalance, which were then followed by the deployment of an osmoregulation method. Throughout the osmoregulation process, the plant will acquire organic molecules, such as glycine betaine, amino acids, sugars, quaternary ammonium compounds, and polyols, further lowering osmotic potential [94]. Furthermore, plant membrane malfunction and cellular metabolic impairment are direct consequences of increased Na^+ buildup in salt-stressed plant tissues. Consequently, the raised level of Na^+ ions causes osmotic stress, which leads to a deficiency of water in the cells as well as a decline in water potential [36].

The degree of soil salinity is gradually spreading throughout the world, and salt stress has been demonstrated to lower agricultural production and quality, putting the world's food supply at risk to meet the needs of the expanding population. Several techniques have been applied to modify the ion balance and osmotic homeostasis in order to counteract these negative effects and prevent salt damage [95]. Although recent reports have proven the beneficial effects of nontechnology on crop plants under saline conditions, the link and interplay between NMs and intracellular systems in plants are not completely understood [96]. Thereby, the mechanisms underlying nanotechnology-enabled plant tolerance to salt stress have been dealt with primarily in this section, with a focus on how it has been reported to intervene with preserving ROS homeostasis, striving to improve the plant's ability to exclude Na^+ and retain K^+, intensifying nitric oxide production, increasing amylase activity to ramp up the soluble sugar content, and diminishing lipoxygenase activity to reduce membrane oxidative damage [30,96–98].

In a study, the salinity stress alleviation potential of different NMs, *viz.*, Si, Zn, B, and zeolite, was evaluated in *Solanum tuberosum* L.; plant development, physiology, and yield were investigated in two separate experiments in salt-affected sandy soil under single or combined administration of various NMs. The growth parameters—leaf-relative water content, chlorophyll content, leaf-photosynthetic rate, stomatal conductance, and tuber production—were recorded to be significantly improved by using NMs when compared to the untreated control. Furthermore, the application of these NMs to the soil increased the concentrations of nutrients in plant tissues, proline, and gibberellic acid hormone in leaves, as well as the contents of protein, carbohydrates, and antioxidant enzymes in tubers. In comparison to other treatments, the combined input of NMs demonstrated greater plant growth, physiological responses, transpiration rate, endogenous elements, and the lowest levels of leaf abscisic acid [99]. In another study, the effects of seed priming with various doses of TiO_2NMs (40, 60, and 80 ppm) were analyzed on the germination, growth, and physiological implications in *Z. mays* under salinity stress [100]. The result demonstrated that priming TiO_2NMs at 60 ppm had beneficial effects on *Z. mays* seedling development and germination under salt stress.

By activating particular genes, collecting osmolytes, and giving free nutrients and amino acids, NMs aid in reducing such stressors. Treatment with SiO_2NMs increased the water usage efficiency, enzyme carbonic anhydrase activity, and defensive response to salinity stress in *Cucurbita pepo* [101]. Linolenic acid is hampered by TiO_2 (anatase), which also affects photoreduction activity, in the electron transport chain (ETC) [102]. According to research conducted on the plant *Abelmoschus esculentus*, foliar administration of ZnO NMs enhances the efficiency of the enzymatic system and the photosynthetic machinery to lessen the effects of salinity stress. The efficiency of photosystem II was increased, which had a good effect on plant development and led to improved photosynthesis. Additionally, it aids in maintaining relative water content (RWC), reducing membrane damage [103]. The seedlings of *Mangifera indica* were sprayed with ZnO and Si-based NMs, and nutrient uptake and carbon assimilation were noted to be increased, which led to better growth circumstances [104].

2.2.2. Drought Stress

A significant environmental cue that stunts the development of plants and reduces their overall production is drought stress. Investigative work is being conducted to analyze the potential mitigation strategies for the deleterious effects of drought stress on plants. The use of nanotechnology to the resolution of a broad variety of environmental problems, including drought stress [105]. According to a recent study, the effectiveness of the foliar treatment of ZnO-NPs at 5 and 100 mgL^{-1} on *C. sativus* growth under drought stress was evaluated [106]. Under normal circumstances, ZnO NMs application significantly increased growth and biomass while preventing drought-induced reductions in morpho-physiological parameters. It also resulted in an increase in photosynthetic pigments, photosynthesis, and PSII activity, and the maximal effect was reported at 100 mg L^{-1} of ZnO NMs. The generation of ROS and lipid peroxidation was reduced in plants treated with ZnO NMs, and this significant decrease in oxidative damage was demonstrated by the augmentation of non-enzymatic and enzymatic antioxidant components [106].

Thus, authors revealed that use of exogenous ZnO NMs can be a practical strategy for managing drought stress in crops [106]. In another work, SiO_2NMs were examined for their ability to decrease the stress imposed by water scarcity in micro-propagated *Musa paradisiaca* (cv. Grand Nain). Under laboratory settings, the application of SiO_2NMs increased shoot development and chlorophyll content while decreasing malonaldehyde (MDA) and electrolyte leakage (EL). Simultaneously, it was noticed that *M. paradisiaca* grown in greenhouses with SiO_2NMs had improved photosynthesis, elevated K^+ levels, and lowered Na^+ levels when compared to the control [107]. Apart from ZnO- and SiO_2-TiO_2NMs, others were also reported to provide positive effects on *Lathyrus sativus* L. under drought stress. The application of TiO_2 NMs protected plants against drought stress by improving the germination parameter and growth and development indices when compared to control [108]. Similarly, the applications of TiO_2 NMs to wheat seedlings under drought stress imparted positive effects in comparison to the control. The soil-applied TiO_2 NMs at (2000 mg kg^{-1} enhanced seedling dry weight, RWC, CAT activity, ascorbate peroxidase (APX) activity, and proline content. Additionally, TiO_2 NMs enhanced photosynthesis with associated parameters under severe drought stress [109]. Similar outcomes were shown with *Triticum aestivum*, which increased starch and gluten content, enhancing growth and yield in drought-stricken conditions [110]. Through the production of proline and subsequent regulation of the amount of proline, *Corchorus* seeds treated with Ca-based NMs (hydroxyapatite nanoparticles) demonstrated better tolerance against drought stress [111]. While treatment with yttrium-doped Fe_2O_3 NMs enhanced photosynthetic machinery with increased chlorophyll and carotenoid content and lessened the harmful effects of drought on *B. napus*, despite the fact that drought stress severely hinders corn seedlings and slows their growth [112].

Studies on *Z. mays* showed that micro-ZnO slows down the breakdown of photosynthetic pigment, increasing the rate of photosynthesis and stomatal activity. By modifying important enzymes, including UDP glucose pyrophosphorylase, phosphoglucoisomerase, and cytoplasmic invertase, greater performance under drought stress was also achieved [113]. As a result, ZnO NMs has the potential as a nanoagent to lessen the impacts of drought stress. According to Van Nguyen et al. [114], CuO-based NMs help *Z. mays* cope with drought stress by positively regulating the pigment system and ROS scavenging mechanisms. It has been discovered that applying the same NMs at low dose to roots and leaves enhances crop performance by increasing the activity of photosynthetic enzymes, such as RuBisCO and chlorophyll, which leads to increased photosynthesis. Additionally, it promotes supplement uptake, strengthens stress resistance, and has a favorable effect on yield.

2.2.3. Availability of Nutrients

Both precision farming and sustainable crop yields depend on effective pesticide delivery mechanisms into plant cells. In conventional methods, agrochemicals are typically delivered to crops by spraying, sprinklers, or furrow irrigation, which can occasionally result in nutrient loss or excessive nutrient application, both of which have long-term consequences on the health of the soil [115]. Fertilizers currently contribute approximately 50% of agricultural productivity; however, the growing usage of higher dosages of fertilizers does not ensure increased crop yield and instead causes a number of issues such as soil degradation and pollution of surface and underground water resources [116]. Plus, due to chemical leaching loss, drift, runoff, hydrolysis, evaporation, photolysis, or even microbiological deterioration, a very little amount, far below the minimum necessary concentration, reaches the plants [117].

Nanofertilizers contain a large surface and particles that are smaller than the pores in a plant's root system and leaves, which can boost their penetration into the plants as well as nutrient usage efficiency [118]. The use of fertilizers encapsulated in NMs has been shown to improve the bioavailability and uptake of nutrients by crop plants [119]. The ability of zeolite-based nanofertilizers to progressively give nutrients to agricultural plants boosts the crop's nutrient supply during the growing season and decreases nutrient loss due to volatilization, leaching, denitrification, and soil fixation [120]. The effects of TiO_2-based NMs at 500 and 750 mg kg^{-1} on *O. sativa* growth and nutrient availability under various soil textures (sandy loam, silt loam, and silty clay loam) were examined in a study [121]. The addition of 500 mg kg^{-1} TiO_2 NMs to silty-clay loam soil increased the amount of plant-chlorophyll, the length of the shoots and roots, and their biomass when compared to other soil textures [121]. According to the study, Ca, Fe, and P are the main nutrients that cause an increase in plant biomass and length when exposed to TiO_2 NMs, suggesting that TiO_2 NMs may have a positive impact on these nutrients' availability [121]. Another study evaluated the effectiveness of urea-modified hydroxyapatite NMs for controlled release of nitrogen [122]. The observations revealed that an initial rapid release of N from nanofertilizers was followed by a sustained release over the next 60 days [122]. Comparatively, traditionally manufactured Ag NMs, green Ag NMs (GS-NPs) made from plant leaf extract of *Thuja occidentalis* were examined for their impact on soil physicochemical parameters and crop growth [123]. Significant increases in water holding capacity, cation exchange capacity, and N/P availability were seen after the application of GS-NMs, which also caused the pH of the soil to shift in the direction of neutrality. Green Ag NMs treated soils efficiently resisted nitrate leaching, sustaining N availability in soil layers beneath the root zone, as was the mechanism underlying improved availability of N in laboratory settings [123]. The summary of the other recently published literature on the ameliorative effects of different NMs on soil stressors along with plant growth benefits is presented in Table 1.

Table 1. Summary on the roles of nanotechnology for growth and development-associated benefits to the plants under soil stress.

Nanoparticles	Concentration	Plants and Application Mode	Beneficial Effects on Plants	Reference
ZnO-NMs	20, 40, and 60mg L^{-1} [*w*/*v*]	*Lupinus termis*; seed priming	Treatment with ZnO-NMs improved the growth of plants under salinity stress. Increased the contents of photosynthetic pigments, organic solutes, total phenols, and ascorbic acid. Additionally, showed an increment in the activities of SOD, CAT, POD, and APX enzymes. While ZnO-NMs seed priming resulted in a decrement in MDA and Na contents in salt-stressed plants. Thus, seed priming with ZnO-NMs at 60 mg L^{-1} was revealed as an effective method to enhance the salt tolerance of lupine plants.	[124]

Table 1. *Cont.*

Nanoparticles	Concentration	Plants and Application Mode	Beneficial Effects on Plants	Reference
Si NMs	100, 200, 300 and 400 mg kg^{-1} [*w*/*w*]	*Cucumis sativus* var (Beit Alpha); the suspension was directly added to the soil	Regardless of the amount of water given, Si NMs increased cucumber growth and production. The application of Si NMs at a rate of 200 mg kg^{-1} demonstrated the greatest improvement, particularly when cucumber plants received 85% of their evapotranspiration, leading to an increase in morphological parameters when compared to the control.	[101]
ZnO-NMs	1, 3, and 5 mg kg^{-1} [*w*/*w*]	*Sorghum bicolor* var. 251	ZnO-NMs (5 mg kg^{-1}) increased grain N translocation in comparison to drought conditions and restored total N levels to normal. While grain P translocation was restricted by drought, shoot absorption of phosphorus was promoted. However, ZnO-NMs decreased overall P acquisition during stress by drought.	[125]
Poly(acrylic acid)-coated cerium oxide nanoparticles (PNC)	–	*Gossypium hirsutum* L.; seed priming	PNC significantly improved the morphometric parameters by increasing the length, fresh weight, and dry weight of roots, modifying root anatomical structure, and increasing root vitality under salt stress compared to controls. Furthermore, treatment with PNC reduced ROS accumulation in plants.	[126]
Functional carbonnanodots (FCNs)	0, 1, 3, 10, and 30 mg kg^{-1} [*w*/*w*]	*Solanum lycopersicum*; supplemented in soil	Treatments with FCNs improved plant growth, development, and production under drought stress by enhancing physiological plant functions such as photosynthesis, the antioxidant system, osmotic adjustment, etc. FCNs assist to increase root vigor and osmolytes levels, which in turn moderates the decrease in tissue water content and water usage efficiency.	[127]
SiO_2 NMs	150 mg kg^{-1} [*w*/*w*]	*Triticum aestivum* L.	Under drought stress, nano-silica improved the germination percentage, germination index, and germination vigor index. Increased shoot length and root length. Additionally, nano-silica boosted the concentration of photosynthetic pigments, osmolytes, relative water, membrane stability index, phenol, and flavonoids. The use of nano-silica significantly increased antioxidant activity. Compared to control, it also boosted indole acetic acid and cytokinin. Under stressful circumstances, a rise in hundred-grain weight and grains per spike due to the application of nano-silica was seen.	[128]
Zero-valent copper nanoparticles (n-Cuo)	–	*Zea mays*; seed priming	When compared to plants under drought stress, n-Cuo treatment boosted the anthocyanin, chlorophyll, and carotenoid levels. Under drought-stress settings, applying n-Cuo to the plant enhanced overall seed production and grain yield. Thus, this study revealed seed priming with n-Cuo as a potential strategy for the development of drought-tolerant agricultural plants via the regulation of plant defensive mechanisms linked to drought tolerance.	[114]
ZnO-NMs	0, 5, 10, 15, 25 and 50 ppm	*Oryza sativa*	Priming with ZnO-NMs at 25 ppm increased seed and straw yield under water deficit conditions. Additionally, seed priming with ZnO-NMs alleviated the oxidative stress.	[129]

Table 1. *Cont.*

Nanoparticles	Concentration	Plants and Application Mode	Beneficial Effects on Plants	Reference
BioSe-NMs	0, 5, 50, 100, and 150 µmol L^{-1}	*Brassica napus* L.	The most effective concentration of bioSe-NMs was 150 µmol/L against the salinity stress in rapeseed seedlings. The applications of bioSe-NMs mainly imparted positive effects on seedlings under salinity stress via enhancing the germination, adjusting osmotic homeostasis, and switching on enzymatic and on-enzymatic defense systems.	[130]
Iron oxide (IO) NMs	0, 25, 50, and 100 ppm	*Linum usitatissimum* L.	Seed priming with IO-NMs improved the plant's growth and activities of antioxidative enzymes under water stress. Seed priming using IO-NMs also enhanced yield parameters such as the number of fruit branches, capsules, seeds/capsule, and total fresh and dry stem fiber production.	[131]
Engineered Carbon Nanoparticles (CNPs)	25–200 µmol L^{-1}	*Vigna radiata* L.	CNPs improved growth by improving the content of total chlorophyll, protein, and plant biomass in *Vigna radiata*.	[132]
Carbon nanotubes (CNTs)	0, 25, 75, and 125 mg pot^{-1}	*Nicotiana tabacum*	The plant height increased by 6.33%, 10.56%, and 10.00%, and the leaf area increased by 6.64%, 19.51%, and 21.58% at the maturity stage. It also improved the contents of chlorophyll and soluble proteins in leaves.	[133]
CNTs	50, 250, and 500 mg L^{-1}	*Solanum lycopersicum*	CNTs as a seed primer coped with the saline stress and improved the antioxidant defense system, and in combination with GP enhanced the chlorophylls (9.1–21.7%), ascorbic acid (19.5%), glutathione (≈13%), proteins (9.9–11.9%), and phenols (14.2%) in leaves.	[134]
Single-walled CNTs	50–800 µg mL^{-1}	*Hyoscyamus niger*	A reduction in oxidative damage indices and electrolyte leakage, and activate the defense system. Improved water absorption, protein biosynthesis, phenolics, and proline under drought-stress conditions.	[135]

3. Future Aspects

By tackling major issues such as starvation, poverty, and ensuring food safety through enhancing soil health and sustainable crop production, nanotechnology makes it possible to meet sustainable development goals. The potential of nanotechnology spurs a new green revolution by lowering the hazards associated with farming. Despite having countless uses, nanotechnology has not yet been fully utilized, particularly in the agricultural and related sectors. To better understand the relationship between plants and microorganisms and to lessen the stressors that the soil places on plants, NMs can be applied to agriculture. There has not been much research into how nanotechnology might alter or enhance the structure and functionality of the rhizospheric microbiome because there are not many experiments that can be conducted under realistic conditions. In order to improve soil properties and manage soil stresses such as sudden increases in heat, drought, salinity, the lack of nutrients, and toxic elements to increase crop production in a sustainable manner, it is important to understand the precise role that NMs play in enhancing the microbial community. The safe application of the nano-enabled product in agriculture might be guaranteed by a deeper comprehension of the ecological behavior of NMs in combination with soil biota. Additionally, because NMs can have toxic effects at higher doses, it is important to thoroughly examine the interactions between plants and NMs at different levels prior to application in agriculture in order to minimize phytotoxic effects and maintain soil health. The in-depth understanding of the interactions between NMs, plants, and soil microbes as well as the potential concentration of NMs application could improve crop productivity and be useful to reduce the significant input of traditional or chemical fertilizers. The beneficial impact of NMs in reducing the biotic and abiotic stress-induced alterations in crops has been outlined and supported by numerous studies. Since every technology has drawbacks and advantages of its own, nanotechnologies are still necessary in many applications to translate theoretical concepts into workable, real-world applications. The fate of NMs in a practical environment is a worry, and the input of nano-enabled items should be controlled until gaps in knowledge are filled. As a result, the ecological issues of NMs cannot be overlooked. As a result, additional long-term experimental studies are required to identify bottlenecks, narrow the harmful effects, and maximize the benefits of NMs. A critical assessment of the benefits and drawbacks of nanotechnology implementations would be a suitable first step before moving further with it for soil health and crop enhancement. In an agro-ecosystem, NMs begin to undergo multiple bio- and geo-transformations, which may result in the production of a new potentially toxic NMs combination pollutant by interacting with bio-macromolecules found in living systems and habitats.

4. Conclusions

The current review examines how to cope with diverse soil stressors and produce crops in a sustainable manner. The data presented here show the potential of NMs in soils to improve microorganisms or agriculturally significant microbes and promote their functioning in order to improve biodegradation of pollutants or reduce soil pressures. Global soil health degradation is becoming a serious concern in meeting human requirements, particularly food security. The incorporation of NMs into biological processes aids in the cleanup of polluted soils. The incorporation of nanotechnology into diverse methodologies has opened up new avenues for increasing soil health and agricultural output. As a result, this review will be useful for discovering novel nanotechnologies (NMs) with biological and agricultural applications, as well as for researching feasible uses of NMs in soil pollution cleanup programs.

Author Contributions: Conceptualization, V.D.R., A.K. and S.K.U.; methodology, V.D.R.; software, S.K.U.; validation, T.M., S.S. and S.M.; formal analysis, P.R.; investigation, M.B.; resources, T.M.; data curation, S.K.U.; writing—original draft preparation, V.D.R., A.K., E.K., E.K. and S.K.U.; writing—review and editing, A.R., J.S., E.K. and K.K.V.; visualization, S.M.; supervision, T.M.; project administration, V.D.R.; funding acquisition, T.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The present work is supported by the laboratory «Soil Health» of the Southern Federal University with the financial support of the Ministry of Science and Higher Education of the Russian Federation, agreement No. 075-15-2022-1122, and by the grant of the President of the Russian Federation № MK-4654.2022.1.5.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Strer, M.; Svoboda, N.; Herrmann, A. Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany. *Environ. Sci. Eur.* **2018**, *30*, 10. [CrossRef] [PubMed]
2. Raza, A.; Razzaq, A.; Mehmood, S.S.; Zou, X.; Zhang, X.; Lv, Y.; Xu, J. Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. *Plants* **2019**, *8*, 34. [CrossRef] [PubMed]
3. Rajput, V.D.; Minkina, T.; Upadhyay, S.K.; Kumari, A.; Ranjan, A.; Mandzhieva, S.; Sushkova, S.; Singh, R.K.; Verma, K.K. Nanotechnology in the Restoration of Polluted Soil. *Nanomaterials* **2022**, *12*, 769. [CrossRef] [PubMed]
4. Maiti, R.K.; Satya, P. Research advances in major cereal crops for adaptation to abiotic stresses. *GM Crop. Food* **2014**, *5*, 259–279. [CrossRef] [PubMed]

5. Prasad, R.; Bhattacharyya, A.; Nguyen, Q.D. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Front. Microbiol.* **2017**, *8*, 1014. [CrossRef]
6. Rajput, V.D.; Singh, A.; Singh, V.K.; Minkina, T.M.; Sushkova, S. Impact of nanoparticles on soil resource. In *Nanomaterials for Soil Remediation*; Amrane, A., Mohan, D., Nguyen, T.A., Assadi, A.A., Yasin, G., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 65–85.
7. Kalwani, M.; Chakdar, H.; Srivastava, A.; Pabbi, S.; Shukla, P. Effects of nanofertilizers on soil and plant-associated microbial communities: Emerging trends and perspectives. *Chemosphere* **2022**, *287*, 132107. [CrossRef] [PubMed]
8. Khan, S.T.; Adil, S.F.; Shaik, M.R.; Alkhathlan, H.Z.; Khan, M.; Khan, M. Engineered Nanomaterials in Soil: Their Impact on Soil Microbiome and Plant Health. *Plants* **2022**, *11*, 109. [CrossRef]
9. Alabresm, A.; Chen, Y.P.; Decho, A.W.; Lead, J. A novel method for the synergistic remediation of oil-water mixtures using nanoparticles and oil-degrading bacteria. *Sci. Total Environ.* **2018**, *630*, 1292–1297. [CrossRef]
10. Mahmoud, M.E.; Abdou, A.E.H.; Mohamed, S.M.S.; Osman, M.M. Engineered staphylococcus aureus via immobilization on magnetic Fe3O4-phthalate nanoparticles for biosorption of divalent ions from aqueous solutions. *J. Environ. Chem. Eng.* **2016**, *4*, 3810–3824. [CrossRef]
11. Baragaño, D.; Forján, R.; Welte, L.; Gallego, J.L.R. Nanoremediation of As and metals polluted soils by means of graphene oxide nanoparticles. *Sci. Rep.* **2020**, *10*, 1896. [CrossRef]
12. Cao, Y.; Zhang, S.; Zhong, Q.; Wang, G.; Xu, X.; Li, T.; Wang, L.; Jia, Y.; Li, Y. Feasibility of nanoscale zero-valent iron to enhance the removal efficiencies of heavy metals from polluted soils by organic acids. *Ecotoxicol. Environ. Saf.* **2018**, *162*, 464–473. [CrossRef] [PubMed]
13. Wang, Y.; Fang, Z.; Kang, Y.; Tsang, E.P. Immobilization and phytotoxicity of chromium in contaminated soil remediated by CMC-stabilized nZVI. *J. Hazard. Mater.* **2014**, *275*, 230–237. [CrossRef] [PubMed]
14. Elsawy, H.; El-shahawy, A.; Ibrahim, M.; El-Halim, A.E.; Talha, N.; Sedky, A.; Alfwuaires, M.; Alabbad, H.; Almeri, N.; Mahmoud, E. Properties of Recycled Nanomaterials and Their Effect on Biological Activity and Yield of Canola in Degraded Soils. *Agriculture* **2022**, *12*, 2096. [CrossRef]
15. Zhao, F.; Xin, X.; Cao, Y.; Su, D.; Ji, P.; Zhu, Z.; He, Z. Use of carbon nanoparticles to improve soil fertility, crop growth and nutrient uptake by corn (*Zea mays* L.). *Nanomaterials* **2021**, *11*, 2717. [CrossRef] [PubMed]
16. Rajput, V.D.; Minkina, T.; Feizi, M.; Kumari, A.; Khan, M.; Mandzhieva, S.; Sushkova, S.; El-Ramady, H.; Verma, K.K.; Singh, A. Effects of silicon and silicon-based nanoparticles on rhizosphere microbiome, plant stress and growth. *Biology* **2021**, *10*, 791. [CrossRef] [PubMed]
17. Verma, K.K.; Song, X.-P.; Joshi, A.; Tian, D.-D.; Rajput, V.D.; Singh, M.; Arora, J.; Minkina, T.; Li, Y.-R. Recent Trends in Nano-Fertilizers for Sustainable Agriculture under Climate Change for Global Food Security. *Nanomaterials* **2022**, *12*, 173. [CrossRef]
18. Chaudhary, P.; Khati, P.; Chaudhary, A.; Maithani, D.; Kumar, G.; Sharma, A. Cultivable and metagenomic approach to study the combined impact of nanogypsum and Pseudomonas taiwanensis on maize plant health and its rhizospheric microbiome. *PLoS ONE* **2021**, *16*, e0250574. [CrossRef]
19. Rajput, V.D.; Minkina, T.; Sushkova, S.; Tsitsuashvili, V.; Mandzhieva, S.; Gorovtsov, A.; Nevidomskyaya, D.; Gromakova, N. Effect of nanoparticles on crops and soil microbial communities. *J. Soils Sediments* **2018**, *18*, 2179–2187. [CrossRef]
20. Khanna, K.; Kohli, S.K.; Handa, N.; Kaur, H.; Ohri, P.; Bhardwaj, R.; Yousaf, B.; Rinklebe, J.; Ahmad, P. Enthralling the impact of engineered nanoparticles on soil microbiome: A concentric approach towards environmental risks and cogitation. *Ecotoxicol. Environ. Saf.* **2021**, *222*, 112459. [CrossRef]
21. Tian, H.; Kah, M.; Kariman, K. Are Nanoparticles a Threat to Mycorrhizal and Rhizobial Symbioses? A Critical Review. *Front. Microbiol.* **2019**, *10*, 1660. [CrossRef]
22. Pérez-de-Luque, A. Interaction of nanomaterials with plants: What do we need for real applications in agriculture? *Front. Environ. Sci.* **2017**, *5*, 12. [CrossRef]
23. Jacoby, R.; Peukert, M.; Succurro, A.; Koprivova, A.; Kopriva, S. The Role of Soil Microorganisms in Plant Mineral Nutrition—Current Knowledge and Future Directions. *Front. Plant Sci.* **2017**, *8*, 1617. [CrossRef] [PubMed]
24. Fan, W.; Deng, J.; Shao, L.; Jiang, S.; Xiao, T.; Sun, W.; Xiao, E. The rhizosphere microbiome improves the adaptive capabilities of plants under high soil cadmium conditions. *Front. Plant Sci.* **2022**, *13*, 914103. [CrossRef] [PubMed]
25. Yu, Y.; Li, Z.; Liu, Y.; Wang, F.; Liu, Y.; Zhao, J.; Li, Y.; Gao, Y.; Zhu, N. Roles of plant-associated microorganisms in regulating the fate of Hg in croplands: A perspective on potential pathways in maintaining sustainable agriculture. *Sci. Total Environ.* **2022**, *834*, 155204. [CrossRef]
26. Jatav, H.S.; Sharma, L.D.; Sadhukhan, R.; Singh, S.K.; Singh, S.; Rajput, V.D.; Parihar, M.; Jatav, S.S.; Jinger, D.; Kumar, S.; et al. An Overview of Micronutrients: Prospects and Implication in Crop Production. In *Plant Micronutrients: Deficiency and Toxicity Management*; Aftab, T., Hakeem, K.R., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 1–30.
27. Lal, R. Soil health and carbon management. *Food Energy Secur.* **2016**, *5*, 212–222. [CrossRef]
28. Chung, H.; Kim, M.J.; Ko, K.; Kim, J.H.; Kwon, H.-a.; Hong, I.; Park, N.; Lee, S.-W.; Kim, W. Effects of graphene oxides on soil enzyme activity and microbial biomass. *Sci. Total Environ.* **2015**, *514*, 307–313. [CrossRef] [PubMed]
29. Yasmin, H.; Mazher, J.; Azmat, A.; Nosheen, A.; Naz, R.; Hassan, M.N.; Noureldeen, A.; Ahmad, P. Combined application of zinc oxide nanoparticles and biofertilizer to induce salt resistance in safflower by regulating ion homeostasis and antioxidant defence responses. *Ecotoxicol. Environ. Saf.* **2021**, *218*, 112262. [CrossRef]

30. Rajput, V.D.; Minkina, T.; Kumari, A.; Singh, V.K.; Verma, K.K.; Mandzhieva, S.; Sushkova, S.; Srivastava, S.; Keswani, C. Coping with the challenges of abiotic stress in plants: New dimensions in the field application of nanoparticles. *Plants* **2021**, *10*, 1221. [CrossRef]
31. Rajput, V.D.; Singh, A.; Minkina, T.; Rawat, S.; Mandzhieva, S.; Sushkova, S.; Shuvaeva, V.; Nazarenko, O.; Rajput, P.; Verma, K.K.; et al. Nano-enabled products: Challenges and opportunities for sustainable agriculture. *Plants* **2021**, *10*, 2727. [CrossRef]
32. Alamri, S.; Nafady, N.A.; El-Sagheer, A.M.; El-Aal, M.A.; Mostafa, Y.S.; Hashem, M.; Hassan, E.A. Current Utility of Arbuscular Mycorrhizal Fungi and Hydroxyapatite Nanoparticles in Suppression of Tomato Root-Knot Nematode. *Agronomy* **2022**, *12*, 671. [CrossRef]
33. Upadhyay, S.K.; Srivastava, A.K.; Rajput, V.D.; Chauhan, P.K.; Bhojiya, A.A.; Jain, D.; Chaubey, G.; Dwivedi, P.; Sharma, B.; Minkina, T. Root Exudates: Mechanistic Insight of Plant Growth Promoting Rhizobacteria for Sustainable Crop Production. *Front. Microbiol.* **2022**, *13*, 916488. [CrossRef] [PubMed]
34. Compant, S.; Samad, A.; Faist, H.; Sessitsch, A. A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *J. Adv. Res.* **2019**, *19*, 29–37. [CrossRef] [PubMed]
35. Upadhyay, S.K.; Chauhan, P.K. Optimization of eco-friendly amendments as sustainable asset for salt-tolerant plant growth-promoting bacteria mediated maize (*Zea mays* L.) plant growth, Na uptake reduction and saline soil restoration. *Environ. Res.* **2022**, *211*, 113081. [CrossRef]
36. Gupta, S.; Schillaci, M.; Walker, R.; Smith, P.M.C.; Watt, M.; Roessner, U. Alleviation of salinity stress in plants by endophytic plant-fungal symbiosis: Current knowledge, perspectives and future directions. *Plant Soil* **2021**, *461*, 219–244. [CrossRef]
37. Singh, P.; Chauhan, P.K.; Upadhyay, S.K.; Singh, R.K.; Dwivedi, P.; Wang, J.; Jain, D.; Jiang, M. Mechanistic Insights and Potential Use of Siderophores Producing Microbes in Rhizosphere for Mitigation of Stress in Plants Grown in Degraded Land. *Front. Microbiol.* **2022**, *13*, 898979. [CrossRef] [PubMed]
38. Berendsen, R.L.; Vismans, G.; Yu, K.; Song, Y.; de Jonge, R.; Burgman, W.P.; Burmølle, M.; Herschend, J.; Bakker, P.A.H.M.; Pieterse, C.M.J. Disease-induced assemblage of a plant-beneficial bacterial consortium. *ISME J.* **2018**, *12*, 1496–1507. [CrossRef]
39. Lucke, M.; Correa, M.G.; Levy, A. The Role of Secretion Systems, Effectors, and Secondary Metabolites of Beneficial Rhizobacteria in Interactions With Plants and Microbes. *Front. Plant Sci.* **2020**, *11*, 589416. [CrossRef]
40. Kumar, S.; Sindhu, S.S.; Kumar, R. Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Curr. Res. Microb. Sci.* **2022**, *3*, 100094. [CrossRef] [PubMed]
41. Jansson, J.K.; Hofmockel, K.S. Soil microbiomes and climate change. *Nat. Rev. Microbiol.* **2020**, *18*, 35–46. [CrossRef]
42. Deng, X.; Zhang, N.; Shen, Z.; Zhu, C.; Liu, H.; Xu, Z.; Li, R.; Shen, Q.; Salles, J.F. Soil microbiome manipulation triggers direct and possible indirect suppression against Ralstonia solanacearum and Fusarium oxysporum. *NPJ Biofilms Microbiomes* **2021**, *7*, 33. [CrossRef]
43. Hunter, P. Plant microbiomes and sustainable agriculture. *EMBO Rep.* **2016**, *17*, 1696–1699. [CrossRef] [PubMed]
44. Chen, Q.; Liu, S. Identification and Characterization of the Phosphate-Solubilizing Bacterium Pantoea sp. S32 in Reclamation Soil in Shanxi, China. *Front. Microbiol.* **2019**, *10*, 2171. [CrossRef] [PubMed]
45. Spaepen, S.; Vanderleyden, J. Auxin and plant-microbe interactions. *Cold Spring Harb. Perspect. Biol.* **2011**, *3*, a001438. [CrossRef] [PubMed]
46. Singh, R.; Behera, M.; Kumar, S. Nano-bioremediation: An Innovative Remediation Technology for Treatment and Management of Contaminated Sites. In *Bioremediation of Industrial Waste for Environmental Safety: Volume II: Biological Agents and Methods for Industrial Waste Management*; Bharagava, R.N., Saxena, G., Eds.; Springer: Singapore, 2020; pp. 165–182.
47. Layet, C.; Auffan, M.; Santaella, C.; Chevassus-Rosset, C.; Montes, M.; Ortet, P.; Barakat, M.; Collin, B.; Legros, S.; Bravin, M.N.; et al. Evidence that Soil Properties and Organic Coating Drive the Phytoavailability of Cerium Oxide Nanoparticles. *Environ. Sci. Technol.* **2017**, *51*, 9756–9764. [CrossRef]
48. Bray, N.; Kao-Kniffin, J.; Frey, S.D.; Fahey, T.; Wickings, K. Soil Macroinvertebrate Presence Alters Microbial Community Composition and Activity in the Rhizosphere. *Front. Microbiol.* **2019**, *10*, 256. [CrossRef]
49. Zhao, L.; Huang, Y.; Hu, J.; Zhou, H.; Adeleye, A.S.; Keller, A.A. 1H NMR and GC-MS Based Metabolomics Reveal Defense and Detoxification Mechanism of Cucumber Plant under Nano-Cu Stress. *Environ. Sci. Technol.* **2016**, *50*, 2000–2010. [CrossRef]
50. Zahra, Z.; Arshad, M.; Rafique, R.; Mahmood, A.; Habib, A.; Qazi, I.A.; Khan, S.A. Metallic Nanoparticle (TiO_2 and Fe_3O_4) Application Modifies Rhizosphere Phosphorus Availability and Uptake by Lactuca sativa. *J. Agric. Food Chem.* **2015**, *63*, 6876–6882. [CrossRef]
51. Oloumi, H.; Soltaninejad, R.; Baghizadeh, A. The comparative effects of nano and bulk size particles of CuO and ZnO on glycyrrhizin and phenolic compounds contents in *Glycyrrhiza glabra* L. seedlings. *Indian J. Plant Physiol.* **2015**, *20*, 157–161. [CrossRef]
52. Zahra, Z.; Waseem, N.; Zahra, R.; Lee, H.; Badshah, M.A.; Mehmood, A.; Choi, H.-K.; Arshad, M. Growth and Metabolic Responses of Rice (*Oryza sativa* L.) Cultivated in Phosphorus-Deficient Soil Amended with TiO_2 Nanoparticles. *J. Agric. Food Chem.* **2017**, *65*, 5598–5606. [CrossRef]
53. Dimkpa, C.O.; McLean, J.E.; Britt, D.W.; Anderson, A.J. Bioactivity and Biomodification of Ag, ZnO, and CuO Nanoparticles with Relevance to Plant Performance in Agriculture. *Ind. Biotechnol.* **2012**, *8*, 344–357. [CrossRef]
54. Chu, B.C.; Garcia-Herrero, A.; Johanson, T.H.; Krewulak, K.D.; Lau, C.K.; Peacock, R.S.; Slavinskaya, Z.; Vogel, H.J. Siderophore uptake in bacteria and the battle for iron with the host; a bird's eye view. *BioMetals* **2010**, *23*, 601–611. [CrossRef] [PubMed]

55. Hider, R.C.; Kong, X. Chemistry and biology of siderophores. *Nat. Prod. Rep.* **2010**, *27*, 637–657. [CrossRef]
56. Barton, L.E.; Quicksall, A.N.; Maurice, P.A. Siderophore-Mediated Dissolution of Hematite (α-Fe_2O_3): Effects of Nanoparticle Size. *Geomicrobiol. J.* **2012**, *29*, 314–322. [CrossRef]
57. Avellan, A.; Auffan, M.; Masion, A.; Levard, C.; Bertrand, M.; Rose, J.; Santaella, C.; Achouak, W. Remote Biodegradation of Ge–Imogolite Nanotubes Controlled by the Iron Homeostasis of *Pseudomonas brassicacearum*. *Environ. Sci. Technol.* **2016**, *50*, 7791–7798. [CrossRef] [PubMed]
58. Dimkpa, C.O.; Merten, D.; Svatos, A.; Büchel, G.; Kothe, E. Siderophores mediate reduced and increased uptake of cadmium by Streptomyces tendae F4 and sunflower (*Helianthus annuus*), respectively. *J. Appl. Microbiol.* **2009**, *107*, 1687–1696. [CrossRef] [PubMed]
59. Brandel, J.; Humbert, N.; Elhabiri, M.; Schalk, I.J.; Mislin, G.L.; Albrecht-Gary, A.M. Pyochelin, a siderophore of Pseudomonas aeruginosa: Physicochemical characterization of the iron(III), copper(II) and zinc(II) complexes. *Dalton Trans.* **2012**, *41*, 2820–2834. [CrossRef]
60. Neubauer, U.; Nowack, B.; Furrer, G.; Schulin, R. Heavy Metal Sorption on Clay Minerals Affected by the Siderophore Desferrioxamine B. *Environ. Sci. Technol.* **2000**, *34*, 2749–2755. [CrossRef]
61. Ray, P.; Lakshmanan, V.; Labbé, J.L.; Craven, K.D. Microbe to Microbiome: A Paradigm Shift in the Application of Microorganisms for Sustainable Agriculture. *Front. Microbiol.* **2020**, *11*, 622926. [CrossRef]
62. Panke-Buisse, K.; Poole, A.C.; Goodrich, J.K.; Ley, R.E.; Kao-Kniffin, J. Selection on soil microbiomes reveals reproducible impacts on plant function. *ISME J.* **2015**, *9*, 980–989. [CrossRef]
63. Santhanam, R.; Luu, V.T.; Weinhold, A.; Goldberg, J.; Oh, Y.; Baldwin, I.T. Native root-associated bacteria rescue a plant from a sudden-wilt disease that emerged during continuous cropping. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, E5013–E5020. [CrossRef]
64. Santos, L.F.; Olivares, F.L. Plant microbiome structure and benefits for sustainable agriculture. *Curr. Plant Biol.* **2021**, *26*, 100198. [CrossRef]
65. Fitzpatrick, C.R.; Copeland, J.; Wang, P.W.; Guttman, D.S.; Kotanen, P.M.; Johnson, M.T.J. Assembly and ecological function of the root microbiome across angiosperm plant species. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, E1157–E1165. [CrossRef] [PubMed]
66. Gottschalk, F.; Kost, E.; Nowack, B. Engineered nanomaterials in water and soils: A risk quantification based on probabilistic exposure and effect modeling. *Environ. Toxicol. Chem.* **2013**, *32*, 1278–1287. [CrossRef]
67. Moll, J.; Klingenfuss, F.; Widmer, F.; Gogos, A.; Bucheli, T.D.; Hartmann, M.; van der Heijden, M.G.A. Effects of titanium dioxide nanoparticles on soil microbial communities and wheat biomass. *Soil Biol. Biochem.* **2017**, *111*, 85–93. [CrossRef]
68. Grün, A.-L.; Manz, W.; Kohl, Y.L.; Meier, F.; Straskraba, S.; Jost, C.; Drexel, R.; Emmerling, C. Impact of silver nanoparticles (AgNP) on soil microbial community depending on functionalization, concentration, exposure time, and soil texture. *Environ. Sci. Eur.* **2019**, *31*, 15. [CrossRef]
69. Johansen, A.; Pedersen, A.L.; Jensen, K.A.; Karlson, U.; Hansen, B.M.; Scott-Fordsmand, J.J.; Winding, A. Effects of C60 fullerene nanoparticles on soil bacteria and protozoans. *Environ. Toxicol. Chem.* **2008**, *27*, 1895–1903. [CrossRef] [PubMed]
70. Grün, A.-L.; Straskraba, S.; Schulz, S.; Schloter, M.; Emmerling, C. Long-term effects of environmentally relevant concentrations of silver nanoparticles on microbial biomass, enzyme activity, and functional genes involved in the nitrogen cycle of loamy soil. *J. Environ. Sci.* **2018**, *69*, 12–22. [CrossRef]
71. Liu, J.; Williams, P.C.; Geisler-Lee, J.; Goodson, B.M.; Fakharifar, M.; Peiravi, M.; Chen, D.; Lightfoot, D.A.; Gemeinhardt, M.E. Impact of wastewater effluent containing aged nanoparticles and other components on biological activities of the soil microbiome, Arabidopsis plants, and earthworms. *Environ. Res.* **2018**, *164*, 197–203. [CrossRef]
72. Kibbey, T.C.G.; Strevett, K.A. The effect of nanoparticles on soil and rhizosphere bacteria and plant growth in lettuce seedlings. *Chemosphere* **2019**, *221*, 703–707. [CrossRef]
73. Khodakovskaya, M.V.; Kim, B.S.; Kim, J.N.; Alimohammadi, M.; Dervishi, E.; Mustafa, T.; Cernigla, C.E. Carbon nanotubes as plant growth regulators: Effects on tomato growth, reproductive system, and soil microbial community. *Small* **2013**, *9*, 115–123. [CrossRef]
74. Hao, Y.; Ma, C.; Zhang, Z.; Song, Y.; Cao, W.; Guo, J.; Zhou, G.; Rui, Y.; Liu, L.; Xing, B. Carbon nanomaterials alter plant physiology and soil bacterial community composition in a rice-soil-bacterial ecosystem. *Environ. Pollut.* **2018**, *232*, 123–136. [CrossRef] [PubMed]
75. Doolette, C.L.; Gupta, V.V.; Lu, Y.; Payne, J.L.; Batstone, D.J.; Kirby, J.K.; Navarro, D.A.; McLaughlin, M.J. Quantifying the Sensitivity of Soil Microbial Communities to Silver Sulfide Nanoparticles Using Metagenome Sequencing. *PLoS ONE* **2016**, *11*, e0161979. [CrossRef] [PubMed]
76. Berhe, A.A.; Barnes, R.T.; Six, J.; Marín-Spiotta, E. Role of Soil Erosion in Biogeochemical Cycling of Essential Elements: Carbon, Nitrogen, and Phosphorus. *Annu. Rev. Earth Planet. Sci.* **2018**, *46*, 521–548. [CrossRef]
77. Eivazi, F.; Afrasiabi, Z.; Jose, E. Effects of Silver Nanoparticles on the Activities of Soil Enzymes Involved in Carbon and Nutrient Cycling. *Pedosphere* **2018**, *28*, 209–214. [CrossRef]
78. Zhao, S.; Su, X.; Wang, Y.; Yang, X.; Bi, M.; He, Q.; Chen, Y. Copper oxide nanoparticles inhibited denitrifying enzymes and electron transport system activities to influence soil denitrification and N2O emission. *Chemosphere* **2020**, *245*, 125394. [CrossRef]
79. Priester, J.H.; Ge, Y.; Mielke, R.E.; Horst, A.M.; Moritz, S.C.; Espinosa, K.; Gelb, J.; Walker, S.L.; Nisbet, R.M.; An, Y.-J.; et al. Soybean susceptibility to manufactured nanomaterials with evidence for food quality and soil fertility interruption. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, E2451–E2456. [CrossRef]

80. Judy, J.D.; McNear, D.H., Jr.; Chen, C.; Lewis, R.W.; Tsyusko, O.V.; Bertsch, P.M.; Rao, W.; Stegemeier, J.; Lowry, G.V.; McGrath, S.P.; et al. Nanomaterials in Biosolids Inhibit Nodulation, Shift Microbial Community Composition, and Result in Increased Metal Uptake Relative to Bulk/Dissolved Metals. *Environ. Sci. Technol.* **2015**, *49*, 8751–8758. [CrossRef]
81. Zhang, L.; Wu, L.; Si, Y.; Shu, K. Size-dependent cytotoxicity of silver nanoparticles to Azotobacter vinelandii: Growth inhibition, cell injury, oxidative stress and internalization. *PLoS ONE* **2018**, *13*, e0209020. [CrossRef]
82. Khan, S.S.; Mukherjee, A.; Chandrasekaran, N. Impact of exopolysaccharides on the stability of silver nanoparticles in water. *Water Res.* **2011**, *45*, 5184–5190. [CrossRef]
83. Lin, D.; Drew Story, S.; Walker, S.L.; Huang, Q.; Cai, P. Influence of extracellular polymeric substances on the aggregation kinetics of TiO2 nanoparticles. *Water Res.* **2016**, *104*, 381–388. [CrossRef]
84. Xiao, Y.; Huang, Q.; Zheng, Z.; Guan, H.; Liu, S. Construction of a Cordyceps sinensis exopolysaccharide-conjugated selenium nanoparticles and enhancement of their antioxidant activities. *Int. J. Biol. Macromol.* **2017**, *99*, 483–491. [CrossRef]
85. Amde, M.; Liu, J.F.; Tan, Z.Q.; Bekana, D. Transformation and bioavailability of metal oxide nanoparticles in aquatic and terrestrial environments. A review. *Environ. Pollut.* **2017**, *230*, 250–267. [CrossRef] [PubMed]
86. Backer, R.; Rokem, J.S.; Ilangumaran, G.; Lamont, J.; Praslickova, D.; Ricci, E.; Subramanian, S.; Smith, D.L. Plant Growth-Promoting Rhizobacteria: Context, Mechanisms of Action, and Roadmap to Commercialization of Biostimulants for Sustainable Agriculture. *Front. Plant Sci.* **2018**, *9*, 1473. [CrossRef] [PubMed]
87. Ahkami, A.H.; Allen White, R.; Handakumbura, P.P.; Jansson, C. Rhizosphere engineering: Enhancing sustainable plant ecosystem productivity. *Rhizosphere* **2017**, *3*, 233–243. [CrossRef]
88. Khan, N.; Bano, A.; Babar, M.D.A. Metabolic and physiological changes induced by plant growth regulators and plant growth promoting rhizobacteria and their impact on drought tolerance in *Cicer arietinum* L. *PLoS ONE* **2019**, *14*, e0213040. [CrossRef] [PubMed]
89. Hakim, S.; Naqqash, T.; Nawaz, M.S.; Laraib, I.; Siddique, M.J.; Zia, R.; Mirza, M.S.; Imran, A. Rhizosphere Engineering With Plant Growth-Promoting Microorganisms for Agriculture and Ecological Sustainability. *Front. Sustain. Food Syst.* **2021**, *5*, 617157. [CrossRef]
90. Linh, T.M.; Mai, N.C.; Hoe, P.T.; Lien, L.Q.; Ban, N.K.; Hien, L.T.T.; Chau, N.H.; Van, N.T. Metal-Based Nanoparticles Enhance Drought Tolerance in Soybean. *J. Nanomater.* **2020**, *2020*, 4056563. [CrossRef]
91. Djanaguiraman, M.; Belliraj, N.; Bossmann, S.H.; Prasad, P.V.V. High-Temperature Stress Alleviation by Selenium Nanoparticle Treatment in Grain Sorghum. *ACS Omega* **2018**, *3*, 2479–2491. [CrossRef]
92. Ali, B.; Wang, X.; Saleem, M.H.; Hafeez, A.; Afridi, M.S.; Khan, S.; Alatawi, A.; Ullah, I.; Amaral Júnior, A.T.d.; Ali, S.; et al. PGPR-Mediated Salt Tolerance in Maize by Modulating Plant Physiology, Antioxidant Defense, Compatible Solutes Accumulation and Bio-Surfactant Producing Genes. *Plants* **2022**, *11*, 345. [CrossRef]
93. Osman, H.S.; Gowayed, S.M.; Elbagory, M.; Omara, A.E.; El-Monem, A.M.A.; Abd El-Razek, U.A.; Hafez, E.M. Interactive Impacts of Beneficial Microbes and Si-Zn Nanocomposite on Growth and Productivity of Soybean Subjected to Water Deficit under Salt-Affected Soil Conditions. *Plants* **2021**, *10*, 1396. [CrossRef]
94. Farooq, M.; Gogoi, N.; Hussain, M.; Barthakur, S.; Paul, S.; Bharadwaj, N.; Migdadi, H.M.; Alghamdi, S.S.; Siddique, K.H.M. Effects, tolerance mechanisms and management of salt stress in grain legumes. *Plant Physiol. Biochem.* **2017**, *118*, 199–217. [CrossRef] [PubMed]
95. Chauhan, P.K.; Upadhyay, S.K.; Tripathi, M.; Singh, R.; Krishna, D.; Singh, S.K.; Dwivedi, P. Understanding the salinity stress on plant and developing sustainable management strategies mediated salt-tolerant plant growth-promoting rhizobacteria and CRISPR/Cas9. *Biotechnol. Genet. Eng. Rev.* **2022**, 1–37. [CrossRef] [PubMed]
96. Etesami, H.; Fatemi, H.; Rizwan, M. Interactions of nanoparticles and salinity stress at physiological, biochemical and molecular levels in plants: A review. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112769. [CrossRef]
97. Karami, A.; Sepehri, A. Beneficial role of MWCNTs and SNP on growth, physiological and photosynthesis performance of barley under NaCl stress. *J. Soil Sci. Plant Nutr.* **2018**, *18*, 752–771. [CrossRef]
98. Zulfiqar, F.; Ashraf, M. Nanoparticles potentially mediate salt stress tolerance in plants. *Plant Physiol. Biochem.* **2021**, *160*, 257–268. [CrossRef] [PubMed]
99. Mahmoud, A.W.M.; Abdeldaym, E.A.; Abdelaziz, S.M.; El-Sawy, M.B.I.; Mottaleb, S.A. Synergetic Effects of Zinc, Boron, Silicon, and Zeolite Nanoparticles on Confer Tolerance in Potato Plants Subjected to Salinity. *Agronomy* **2020**, *10*, 19. [CrossRef]
100. Basahi, M. Seed germination with titanium dioxide nanoparticles enhances water supply, reserve mobilization, oxidative stress and antioxidant enzyme activities in pea. *Saudi J. Biol. Sci.* **2021**, *28*, 6500–6507. [CrossRef]
101. Alsaeedi, A.; El-Ramady, H.; Alshaal, T.; El-Garawany, M.; Elhawat, N.; Al-Otaibi, A. Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake. *Plant Physiol. Biochem.* **2019**, *139*, 1–10. [CrossRef]
102. Su, M.; Liu, C.; Qu, C.; Zheng, L.; Chen, L.; Huang, H.; Liu, X.; Wu, X.; Hong, F. Nano-anatase relieves the inhibition of electron transport caused by linolenic acid in chloroplasts of spinach. *Biol. Trace Elem. Res.* **2008**, *122*, 73–81. [CrossRef]
103. Alabdallah, N.M.; Hasan, M.M. Plant-based green synthesis of silver nanoparticles and its effective role in abiotic stress tolerance in crop plants. *Saudi J. Biol. Sci.* **2021**, *28*, 5631–5639. [CrossRef]
104. Elsheery, N.I.; Helaly, M.N.; El-Hoseiny, H.M.; Alam-Eldein, S.M. Zinc Oxide and Silicone Nanoparticles to Improve the Resistance Mechanism and Annual Productivity of Salt-Stressed Mango Trees. *Agronomy* **2020**, *10*, 558. [CrossRef]

105. Kumari, A.; Kaur, R.; Kaur, R. An insight into drought stress and signal transduction of abscisic acid. *Plant Sci. Today* **2018**, *5*, 72–80. [CrossRef]
106. Ghani, M.I.; Saleem, S.; Rather, S.A.; Rehmani, M.S.; Alamri, S.; Rajput, V.D.; Kalaji, H.M.; Saleem, N.; Sial, T.A.; Liu, M. Foliar application of zinc oxide nanoparticles: An effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. *Chemosphere* **2022**, *289*, 133202. [CrossRef]
107. Mahmoud, L.M.; Dutt, M.; Shalan, A.M.; El-Kady, M.E.; El-Boray, M.S.; Shabana, Y.M.; Grosser, J.W. Silicon nanoparticles mitigate oxidative stress of in vitro-derived banana (*Musa acuminata* 'Grand Nain') under simulated water deficit or salinity stress. *S. Afr. J. Bot.* **2020**, *132*, 155–163. [CrossRef]
108. Hojjat, S.S. Effects of TiO2 Nanoparticles on Germination and Growth Characteristics of Grass Pea (*Lathyrus sativus* L.) Seed under Drought Stress. *Nanotechnol. Russ.* **2020**, *15*, 204–211. [CrossRef]
109. Faraji, J.; Sepehri, A. Exogenous Nitric Oxide Improves the Protective Effects of TiO_2 Nanoparticles on Growth, Antioxidant System, and Photosynthetic Performance of Wheat Seedlings Under Drought Stress. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 703–714. [CrossRef]
110. Jaberzadeh, A.; Moaveni, P.; Tohidi Moghadam, H.R.; Zahedi, H. Influence of Bulk and Nanoparticles Titanium Foliar Application on some Agronomic Traits, Seed Gluten and Starch Contents of Wheat Subjected to Water Deficit Stress. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2013**, *41*, 201–207. [CrossRef]
111. Das, A.; Ray, R.; Mandal, N.; Chakrabarti, K. An analysis of transcripts and enzyme profiles in drought stressed jute (*Corchorus capsularis*) and rice (*Oryza sativa*) seedlings treated with $CaCl_2$, hydroxyapatite nano-particle and β-amino butyric acid. *Plant Growth Regul.* **2016**, *79*, 401–412. [CrossRef]
112. Palmqvist, N.G.M.; Seisenbaeva, G.A.; Svedlindh, P.; Kessler, V.G. Maghemite Nanoparticles Acts as Nanozymes, Improving Growth and Abiotic Stress Tolerance in Brassica napus. *Nanoscale Res. Lett.* **2017**, *12*, 631. [CrossRef]
113. Sun, L.; Song, F.; Guo, J.; Zhu, X.; Liu, S.; Liu, F.; Li, X. Nano-ZnO-Induced Drought Tolerance Is Associated with Melatonin Synthesis and Metabolism in Maize. *Int. J. Mol. Sci.* **2020**, *21*, 782. [CrossRef]
114. Van Nguyen, D.; Nguyen, H.M.; Le, N.T.; Nguyen, K.H.; Nguyen, H.T.; Le, H.M.; Nguyen, A.T.; Dinh, N.T.T.; Hoang, S.A.; Van Ha, C. Copper Nanoparticle Application Enhances Plant Growth and Grain Yield in Maize Under Drought Stress Conditions. *J. Plant Growth Regul.* **2022**, *41*, 364–375. [CrossRef]
115. Hidangmayum, A.; Debnath, A.; Guru, A.; Singh, B.N.; Upadhyay, S.K.; Dwivedi, P. Mechanistic and recent updates in nano-bioremediation for developing green technology to alleviate agricultural contaminants. *Int. J. Environ. Sci. Technol.* **2022**, 1–26. [CrossRef] [PubMed]
116. Shang, Y.; Hasan, M.K.; Ahammed, G.J.; Li, M.; Yin, H.; Zhou, J. Applications of nanotechnology in plant growth and crop protection: A review. *Molecules* **2019**, *24*, 2558. [CrossRef] [PubMed]
117. Nuruzzaman, M.; Rahman, M.M.; Liu, Y.; Naidu, R. Nanoencapsulation, Nano-guard for Pesticides: A New Window for Safe Application. *J. Agric. Food Chem.* **2016**, *64*, 1447–1483. [CrossRef] [PubMed]
118. Hong, J.; Wang, C.; Wagner, D.C.; Gardea-Torresdey, J.L.; He, F.; Rico, C.M. Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts. *Environ. Sci. Nano* **2021**, *8*, 1196–1210. [CrossRef]
119. Khan, M.R.; Rizvi, T.F. Application of Nanofertilizer and Nanopesticides for Improvements in Crop Production and Protection. In *Nanoscience and Plant–Soil Systems*; Ghorbanpour, M., Manika, K., Varma, A., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 405–427.
120. Soltys, L.; Mironyuk, I.; Tatarchuk, T.; Tsinurchyn, V. Zeolite-based Composites as Slow Release Fertilizers (Review). *Phys. Chem. Solid State* **2020**, *21*, 89–104. [CrossRef]
121. Arshad, M.; Nisar, S.; Gul, I.; Nawaz, U.; Irum, S.; Ahmad, S.; Sadat, H.; Mian, I.A.; Ali, S.; Rizwan, M.; et al. Multi-element uptake and growth responses of Rice (*Oryza sativa* L.) to TiO_2 nanoparticles applied in different textured soils. *Ecotoxicol. Environ. Saf.* **2021**, *215*, 112149. [CrossRef]
122. Kottegoda, N.; Munaweera, I.; Madusanka, N.; Karunaratne, V. A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. *Curr. Sci.* **2011**, *101*, 73–78.
123. Das, P.; Barua, S.; Sarkar, S.; Karak, N.; Bhattacharyya, P.; Raza, N.; Kim, K.H.; Bhattacharya, S.S. Plant extract-mediated green silver nanoparticles: Efficacy as soil conditioner and plant growth promoter. *J. Hazard. Mater.* **2018**, *346*, 62–72. [CrossRef]
124. Abdel Latef, A.A.H.; Abu Alhmad, M.F.; Abdelfattah, K.E. The Possible Roles of Priming with ZnO Nanoparticles in Mitigation of Salinity Stress in Lupine (*Lupinus termis*) Plants. *J. Plant Growth Regul.* **2017**, *36*, 60–70. [CrossRef]
125. Dimkpa, C.O.; Singh, U.; Bindraban, P.S.; Elmer, W.H.; Gardea-Torresdey, J.L.; White, J.C. Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. *Sci. Total Environ.* **2019**, *688*, 926–934. [CrossRef]
126. An, J.; Hu, P.; Li, F.; Wu, H.; Shen, Y.; White, J.C.; Tian, X.; Li, Z.; Giraldo, J.P. Emerging investigator series: Molecular mechanisms of plant salinity stress tolerance improvement by seed priming with cerium oxide nanoparticles. *Environ. Sci. Nano* **2020**, *7*, 2214–2228. [CrossRef]
127. Chen, Q.; Cao, X.; Nie, X.; Li, Y.; Liang, T.; Ci, L. Alleviation role of functional carbon nanodots for tomato growth and soil environment under drought stress. *J. Hazard. Mater.* **2022**, *423*, 127260. [CrossRef] [PubMed]
128. Akhtar, N.; Ilyas, N. Role of nanosilicab to boost the activities of metabolites in *Triticum aestivum* facing drought stress. *Plant Soil* **2022**, *477*, 99–115. [CrossRef]

129. Waqas Mazhar, M.; Ishtiaq, M.; Hussain, I.; Parveen, A.; Hayat Bhatti, K.; Azeem, M.; Thind, S.; Ajaib, M.; Maqbool, M.; Sardar, T.; et al. Seed nano-priming with Zinc Oxide nanoparticles in rice mitigates drought and enhances agronomic profile. *PLoS ONE* **2022**, *17*, e0264967. [CrossRef] [PubMed]
130. El-Badri, A.M.; Batool, M.; Mohamed, I.A.A.; Wang, Z.; Wang, C.; Tabl, K.M.; Khatab, A.; Kuai, J.; Wang, J.; Wang, B.; et al. Mitigation of the salinity stress in rapeseed (*Brassica napus* L.) productivity by exogenous applications of bio-selenium nanoparticles during the early seedling stage. *Environ. Pollut.* **2022**, *310*, 119815. [CrossRef] [PubMed]
131. Waqas Mazhar, M.; Ishtiaq, M.; Maqbool, M.; Akram, R.; Shahid, A.; Shokralla, S.; Al-Ghobari, H.; Alataway, A.; Dewidar, A.Z.; El-Sabrout, A.M.; et al. Seed Priming with Iron Oxide Nanoparticles Raises Biomass Production and Agronomic Profile of Water-Stressed Flax Plants. *Agronomy* **2022**, *12*, 982. [CrossRef]
132. Shekhawat, G.S.; Mahawar, L.; Rajput, P.; Rajput, V.D.; Minkina, T.; Singh, R.K. Role of Engineered carbon nanoparticles (CNPs) in promoting growth and metabolism of *Vigna radiata* (L.) Wilczek: Insights into the biochemical and physiological responses. *Plants* **2021**, *10*, 1317. [CrossRef] [PubMed]
133. Liang, T.B.; Yin, Q.S.; Zhang, Y.L.; Wang, B.L.; Guo, W.M.; Wang, J.W.; Xie, J. Effects of carbon nano-particles application on the growth, physiological characteristics and nutrient accumulation in tobacco plants. *J. Food Agric. Environ.* **2013**, *11*, 954–958.
134. González-García, Y.; López-Vargas, E.R.; Pérez-Álvarez, M.; Cadenas-Pliego, G.; Benavides-Mendoza, A.; Valdés-Reyna, J.; Pérez-Labrada, F.; Juárez-Maldonado, A. Seed priming with carbon nanomaterials improves the bioactive compounds of tomato plants under saline stress. *Plants* **2022**, *11*, 1984. [CrossRef]
135. Hatami, M.; Hadian, J.; Ghorbanpour, M. Mechanisms underlying toxicity and stimulatory role of single-walled carbon nanotubes in *Hyoscyamus niger* during drought stress simulated by polyethylene glycol. *J. Hazard. Mater.* **2017**, *324*, 306–320. [CrossRef] [PubMed]