

Biomaterial amendments improve nutrient use efficiency and plant growth

Ying LIU*¹, Natasha MANZOOR*¹, Miao HAN¹, Kun ZHU¹, Gang WANG (✉)^{1,2}

¹ Department of Soil and Water Sciences, China Agricultural University, Beijing 100193, China.

² National Black Soil and Agriculture Research, China Agricultural University, Beijing 100193, China.

*These authors contribute equally to the work

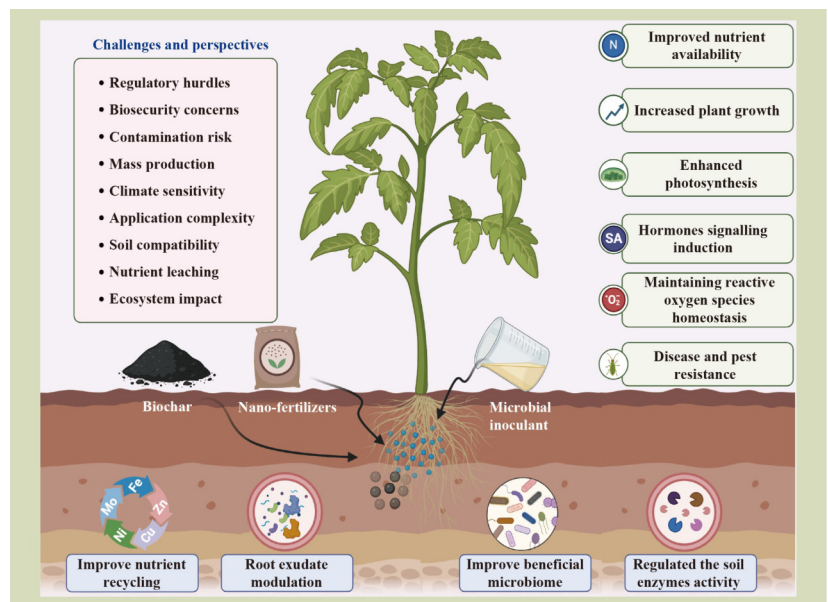
KEYWORDS

Biochar, climate change, food security, microbial inoculant, nanomaterial, soil amendment

HIGHLIGHTS

- Microbial inoculants boost nutrient availability, crop yield, stress resilience and soil remediation.
- Nanomaterials enhance soil fertility, nutrient delivery and mitigate abiotic stresses.
- Biochar acts as an efficient microbial carrier, boosting soil organic carbon.
- Integrating bio-amendments enhances soil health and crop productivity and environmental sustainability.
- Challenges persist in scaling up production, ensuring safe use and understanding long-term impacts.

GRAPHICAL ABSTRACT



ABSTRACT

The achievement of global food security faces exceptional challenges due to the rapid population growth, land degradation and climate change. Current farming practices, including mineral fertilizers and synthetic pesticides, alone are becoming insufficient to ensure long-term food security and ecosystem sustainability. The lack of robustness and reliability of conventional approaches warrants efforts to develop novel alternative strategies. Bio-based management strategies offer promising alternatives for improving soil health and food productivity. For example, microbial inoculants can enhance nutrient availability, crop production and stress resistance while also remediating contaminated soils. Nanobiotechnology is a promising strategy that has great potential for mitigating biotic and abiotic stresses on plant toward sustainable agriculture. Biochar (including modified biochar) serves as an effective microbial carrier, improving nutrient availability and plant growth. Also, biochar amendments have been demonstrated to have great potential

Received February 28, 2024;

Accepted September 19, 2024.

Correspondence: gangwang@cau.edu.cn

facilitating soil organic carbon sequestration and mitigating greenhouse gas emissions and therefore contribute to climate change mitigation efforts. This review examines the integration of microbial inoculants, nano-fertilizers and biochar, which demonstrates as a promising strategy to enhance soil health, crop productivity and environmental sustainability. However, overcoming challenges related to their mass production, application and potential risks remains crucial. Future research should focus on optimizing these bio-amendment strategies, evaluating their economic viability and developing robust regulatory frameworks to ensure safe and effective agricultural implementation.

© The Author(s) 2024. Published by Higher Education Press. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0>)

1 Introduction

With climate change and environmental degradation, a global food crisis is affecting an increasing proportion of the global population. A primary challenge in global agriculture is the sustainable provision of nutrition for the rapidly growing population, which will likely reach 10 billion by 2050 according to a World Health Organization prediction. The increasing probability of adverse agroclimatic conditions exacerbates both biotic and abiotic stressors on agriculture, significantly impacting productivity and soil health^[1]. The agricultural sector currently faces substantial challenges, including the optimization of agrochemical usage, enhancement of crop adaptation and resilience, and improvement of soil productivity and fertility^[2]. Soil amendment management has long been used as a strategy in agriculture to enhance soil health and, subsequently, boost the production of food. The amendments comprise various substances such as microbial inoculants (biofertilizer, bioherbicides, and biopesticides) and nano-fertilizers (metal oxides nanoparticles and nano-scale natural minerals).

Biochar, derived from organic materials such as wheat straw, peanut shells, waste wood, and manure, is another significant soil amendment. This carbon-rich product offers unique properties for soil improvement. Microorganisms, including arbuscular mycorrhizal fungi (AMF), microalgae, and plant growth-promoting bacteria (PGPB), are crucial for sustainable agricultural systems. These beneficial microbes, isolated from plants, water, composted manures, or other organic materials, have been extensively studied^[3]. These beneficial microbes exist in the rhizosphere, where they establish relationships with plant roots. One of the primary functions of PGPB is to promote plant growth. Some PGPB can fix atmospheric nitrogen, converting it into a form that can be readily absorbed by plants, effectively acting as biofertilizers. Others can

solubilize phosphates and essential nutrients from the soil, making them more available to the plants. Additionally, PGPB can produce plant growth regulators, such as auxins, cytokinins, and gibberellins, which stimulate plant growth, root development, and overall plant vigor.

Microbial inoculants, also known as biofertilizers, bioherbicides, biopesticides, and bioremediation agents^[4,5], are composed of living microorganisms. Their multifaceted nature stems from diverse effects on plants, including growth promotion, enhanced seed germination, and pest and disease management^[6]. The application of these inoculants offers a promising approach to sustainable agriculture, potentially reducing reliance on synthetic inputs while enhancing crop productivity and resilience. Also, microbial inoculants contribute substantially to nutrient cycling by enhancing the decomposition of organic matter, mineralization of nutrients and improving nutrient availability to plants. These processes not only support plant growth but also contribute to soil health and sustainability by maintaining a balanced nutrient cycle. The multitude of beneficial impacts associated with microbial inoculants has gained increasing attention within the agricultural sector, leading to their growing prominence and expanding market scale.

Nanotechnology represents a transformative strategy revolutionizing various sectors, including agriculture. Recent advances in nanotechnology have enabled the formation of diverse nanomaterials (NMs), such as nanoparticles (NPs) and nanotubes, which could potentially impact plant rhizosphere microbiome^[7]. These NMs promote plant growth through optimized application procedures and enhance soil physicochemical properties^[8]. For example, the application of nano-fertilizers has been reported to increase crop yield by 10% compared to conventional fertilizers^[9]. Additionally, the use of

NPs has led to increase plant biomass (33.3%) and improve soil nutrient availability^[10]. The NPs can enter the rhizosphere through natural processes, such as plant-mediated mineralization, or through the application of industrially coated nanoparticle products, such as nano-fertilizers^[8,11]. Studies have also shown beneficial effects on soil microbial communities, plant growth and yield^[8].

Biochar is an environmentally persistent material characterized by high carbon content and low oxygen and hydrogen levels. It is produced through thermochemical transformation of organic matter in an oxygen-limited environment. Feedstocks for biochar production include woody residues, crop straw, animal manures, and municipal solid waste^[12]. Over the last two decades, biochar has found widespread application in agriculture, environmental management, and energy sectors due to its cost-effectiveness, sustainability, and associated benefits^[12]. In environmental context, extensive research has been conducted on the use of biochar in the adsorption, degradation, and removal of toxic pollutants. There has been a sustainable growth in related literature, particularly focusing on the sorption of various organic contaminants on biochar, to comprehensively elucidate the underlying mechanisms^[13].

The objective of this review is to evaluate the effects of various biomaterial amendments, specifically microbial inoculants, NMs, and biochar, on soil health and crop production. Additionally, the review aims to explore the potential of these amendments to enhance sustainable agricultural practices, improve food security, and mitigate climate change impacts.

2 Microbial inoculants

More than a century has passed since the production of the first microbial inoculant for plants occurred^[3]. Now the use of microbial inoculants in agriculture is widespread throughout the world for a variety of crops and transporting a variety of microorganisms. Concurrently, abiotic plant stress has increased as a result of global climate change, promoting the development of microbial technologies for conservation and agricultural applications^[14]. Environmental concerns have redirected focus from chemical inputs toward sustainable techniques, such as organic farming and microbial inoculants. Also, recent advances in sequencing and plant-microbiome science has increased investments into microbial inoculants, driven by their demonstrated potential to enhance crop yield^[15]. The subsequent discussion will examine the impact of microbial inoculants on agricultural productivity.

2.1 Enhancing nutrient availability and thus increasing crop yield

Microbial inoculants provide crop with a wide range of nutrients for growth and development, primarily through nitrogen fixation, phosphorus solubilization, and potassium mobilization. Plants mainly absorb nitrogen in the form of nitrate or ammonium ions from the soil to produce amino acids, proteins, nucleic acids, chlorophyll, phytohormones, and many vitamins needed for growth^[16]. However, only a limited number of plants possess the constitutive ability to assimilate atmospheric nitrogen and convert it into a bioavailable form. Nitrogen-fixing microbes (NFM) with the nitrogenase metalloenzyme, such as iron-iron, vanadium-iron, and molybdenum-iron nitrogenases, have ability to convert inert gaseous dinitrogen into plant-available ammonia^[17], thereby supplementing nitrogen nutrition crucial for enhanced crop yield. For example, Huang et al.^[18] demonstrated that the application of bacterial inoculants enhanced growth and nitrogen use efficiency in *Pyrus betulifolia* under nitrogen-limited conditions by modifying the existing soil bacterial communities. In agricultural systems, approximately 80% of BNF contributed by symbiotic association made between leguminous plants and species of *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Rhizobium*, and *Sinorhizobium*^[19].

Also, microbial inoculants have been intensively explored as a sustainable and economical substitute for mineral fertilizers, with a focus on their effects on nutrient availability and crop productivity. Sun et al.^[20] showed that the strategy of substituting 50% urea with biofertilizer reduced the nitrogen loss from farmland soil by 54%, increased nitrogen use efficiency by 11.2% and achieved a 5.0% increase in crop yield. The application of the PSMs as biofertilizers has been proved to positively affect the leaf nutrient content (N, P, and K) of Chinese fir, and increase the total N, P, and K, as well as available P and K content in the soil^[21]. The addition of a *Pseudomonas* as KSB increased K concentration and content by more than 50% and 70% in tomato aerial tissue, respectively. In addition, numerous studies have shown that NFM, PSM, or KSB can be used as microbial inoculants to decrease the use of mineral fertilizers and address nutrient deficiencies^[20,21].

Phosphorus is a vital biogenic element involved in the biosynthesis of various plant compounds, including phytic acid, nucleic acids, and phospholipids. In soil, phosphorus exists primarily in insoluble inorganic and organic forms, but plants mainly absorb it in an anionic form (HPO_4^{2-} or H_2PO_4^-)^[22,23]. The MPKV bacterial consortium improves the

P solubilization by increasing maize plant production^[24]. Phosphate-solubilizing microorganisms (PSMs) have several mechanisms to increase phosphorus bioavailability in soil. They secrete organic acids that lower soil pH, aiding in a dissolution of insoluble phosphates. The PSMs also produce chelating agents that bind cations associated with phosphate compounds, releasing phosphate ions. Additionally, they secrete enzymes like phosphatases and phytases that mineralize organic phosphorus into inorganic forms assimilable by plants. Also, PSMs catalyze the enzymolysis of phosphoric esters, contributing to the liberation of phosphate ions from organic and inorganic sources. Collectively, these mechanisms by PSMs enhance soil phosphorus bioavailability, a crucial factor for optimizing plant growth and productivity^[22]. Potassium is essential for crop growth, involved in vital physiological and biochemical activities such as protein synthesis and nutrient cycling^[21]. In the natural soil ecosystems, potassium is mostly present in a non-exchangeable (fixed) form that is unavailable to plants and bacteria. Potassium solubilizing bacteria (KSB) enhance potassium availability by converting fixed forms into bioavailable forms through acidification and complexation with secreted EPS (e.g., organic and inorganic acids, polysaccharides, and proteins)^[21,25]. Also, wheat inoculated with different bacterial combinations, the plant N content increased from 40.7% to 97.7% ($P < 0.05$). Additionally, the P content of wheat increased from 41.2% to 96.4%, and the K content increased from 2.3% to 42.1%^[26].

Numerous studies have demonstrated that microbial inoculants can significantly improve soil nutrient availability, particularly in the soil-root interface crucial for plant nutrient uptake and yield enhancement^[6]. Root exudates are important carbon sources for soil microorganisms, stimulating microbial colonization near the root surface, enhancing nutrient absorption rates by crops^[27]. Additionally, plants exude a diverse array of secondary metabolites that interact with the surrounding biota, influencing microbial communities and nutrient availability^[28]. The studies conducted by Zhang et al.^[28] observed that *Hansschlegelia zihuaiae* S113 colonized cucumber roots for 20 days, highlighting its potential for sustained nutrient uptake enhancement. Also, research in oats has shown a positive correlation between the ability of a microbe to utilize root exudates and its abundance in underground tissues, underscoring their role in enhancing nutrient availability and supporting plant health^[29]. At that point, rhizosphere microorganisms have an impact on the plant host fitness in diverse manners, such as by aiding in the acquisition of essential nutrients^[29] and providing in biocontrol benefits^[30].

2.2 Improving crops resistance to drought and salinity stress

Abiotic stresses, such as soil salinity, drought and toxic pollutants, are major constraints to agricultural production, influencing crop growth through physiological disorders, hormonal imbalances, and nutritional deficiencies^[5]. Microbial communities interact with crops through direct or indirect mechanisms, regulating crop growth and productivity^[3]. Therefore, the role of microbial inoculants in enhancing crop stress resistance has become increasingly prominent. Soil salinization poses a significant threat to food production and security, affecting arable croplands in over 100 countries. Projections indicate that by 2050, more than 50% of arable lands will be severely affected by salinization^[31]. High soil salinity leads to stunted plant growth, significantly reducing yield and quality. Excessive soluble salts and exchangeable sodium in soil disrupt ion activity, causing nutrient deficiencies and inhibiting overall plant growth and yield. Microbial inoculants ameliorate salt stress through enhanced nutrient uptake, induction of antioxidative defense systems, and reduction of ethylene levels^[31]. Notably, salt stress effects can be diminished by 1-aminocyclopropane-1-carboxylate (ACC) deaminase^[32]. For example, inoculation of pea plants with a strain of *Variovorax paradoxus* that produces ACC deaminase decreased stomatal resistance and xylem balancing pressure, improved photosynthetic efficiency and electron transport rate, balanced ion homeostasis through increased K^+ flow to shoots and Na^+ deposition on roots, and increased biomass under salt stress at 70 and 130 $mmol \cdot L^{-1}$ NaCl^[33]. Additionally, microbial biofilms, particularly extracellular polymeric substances (EPS), maintain and retain high soil moisture, facilitating the availability of dissolved nutrients for plant growth and development, and enhancing plant growth under salinity-induced osmotic stress and nutrient imbalance^[34]. Also, EPS and biofilms can restrict Na^+ uptake by binding and retaining Na^+ in the soil^[34]. Haque et al.^[35] demonstrated that biofilmET-producing rhizobacteria enhanced tomato biomass accumulation through various plant growth-promoting activities, including production of IAA, ACC deaminase, and siderophores, improving nutrient bioavailability, inducing antioxidant defense systems, maintaining higher relative water content, reducing Na^+ uptake and increasing the K^+/Na^+ ratio.

Due to global climate change, drought is becoming increasingly frequent and extreme in most parts of the world. Microbial inoculants can enhance plant drought tolerance through various mechanisms such as decreased stomata conductance, increased nutrient uptake, modulation of antioxidant enzymatic activities and increased hydric content^[6,7]. Arbuscular mycorrhizal inoculants have been reported to

improve tea plant drought tolerance by modulating root architecture such as increasing root volume, number of lateral roots, length of lateral roots and hormones (abscisic acid, brassinosteroids, gibberellins, and indole-3-acetic acid)^[36]. Under drought conditions, microbes can enhance plant physiological and biochemical parameters that aid adaptive plant response, root growths, water content, and plant nutrient content. For example, the combined use of AMF and *Bacillus megaterium* contributed to plant drought tolerance through enhancing plants K⁺ and hydric content, and affecting plant antioxidant activities^[37]. *Pseudomonas putida* ameliorated drought tolerance in chickpea plants by altering various physical, physiological, and biochemical parameters, as well as by reducing expression of stress responsive gene^[38]. The impact of biofertilizers on crop yield and soil health is summarized in Table 1.

2.3 Decontaminating soil toxic pollutants

Soil toxic pollutants, such as heavy metals, petrochemicals, and agrochemicals, pose a key risk to the environment due to the irreversible environmental damage and the long half-live^[51]. Prolonged exposure and higher accumulation of toxic pollutants can have deleterious health effects on human life and soil biota^[51]. The role of microorganisms and plants in removing toxic contaminants from the ecosystem is well-documented, and it has attracted the attention of investigators over the centuries^[52]. Despite being natural components of the environment, heavy metals have emerged as significant threats, having several associated health risks. Microorganisms have different detoxifying mechanisms, such as biotransformation,

biosorption, bioaccumulation, and phytoremediation, which allows them to grow in heavy metal-polluted habitats^[51]. These detoxifying mechanisms work primarily through EPS and cell wall properties. The EPS are macromolecules secreted by various organisms into their environment, and have been reported to be essential in bioremediation of heavy metals^[53]. The microbial cell walls, which mainly consist of polysaccharides, lipids and proteins, offer various functional groups such as that can bind heavy metal ions, and these include carboxylate, hydroxyl, amino and phosphate groups. Biotransformation refers to the conversion of heavy metals into low or non-toxic substances through oxidation/reduction, complexation, methylation and other processes, which changes the state of heavy metals and reduces ecological hazards. The biosorption of heavy metals is divided into intracellular adsorption and extracellular adsorption: Intracellular adsorption means that the heavy metals enter the cell and combine with intracellular molecules to form stable substances, thus accumulating in the cell; Extracellular adsorption refers to the adsorption of heavy metals on the cell surface relying on the cell wall, capsule and surface mucus layer via complexation, precipitation, chelation and ionic interactions^[54]. For example, multiple studies have shown that Cr(VI) can be adsorbed and accumulated near the cell surface, subsequently may act as a terminal electron acceptor getting reduced to Cr(III) and binds to cell wall, which is closely involved in the EPS and cell walls^[42]. Further, Maurya et al.^[55] found that bacterial biofilm (60%–99%) has a greater potential to remove Cr(VI) than planktonic cells (43%–94%).

In addition, organic pollutants including pesticides, polycyclic

Table 1 Impact of biofertilizers on crop yield and soil health

Bacterial species	Crop	Role	Mechanism	Source
<i>Azospirillum brasilense</i>	Rice	Biofertilization	Nitrogen fixation	[39]
<i>Enterobacter oryzae</i>	Mangart and Jam	Biofertilization	Nitrogen fixation	[40]
<i>Pseudomonas putida</i>	Tomato	Biofertilization	Phosphate-Solubilizing	[41]
<i>Pseudomonas fulva</i>	Wheat	Biofertilization	Phosphate solubilization	[42]
<i>Pseudomonas orientalis</i>	Rice	Biofertilization	Potassium solubilization	[43]
<i>Bacillus cereus</i>	Potato	Biofertilization	Potassium solubilization	[44]
<i>Bacillus XZM</i>	<i>Vallisneria denseserrulata</i>	Bioremediation	Biosorption of the heavy metals	[45,46]
<i>Bacillus cereus Alcaligenes faecalis</i>	Sorghum	Bioremediation	Reduction in heavy metals bioaccumulation	[47]
<i>Brevibacterium frigiditolerans</i>	Wheat	Salt stress	Induce resistance against salt stress	[48]
<i>Exiguobacterium</i> sp, <i>Enterobacter</i> sp	Rice	Salt stress	Induce resistance against salt stress	[49]
PGPBs	Wheat	Drought stress	Resistance against drought stress	[49]
<i>Pseudomonas lini Serratia plymuthica</i>	Jujube	Drought stress	Resistance against drought stress	[50]

aromatic hydrocarbons (PAHs) and dyes used in textile and other industries are of significant concern due to their toxic, persistent, carcinogenic and lipophilic nature, as well as bioaccumulation in the food chain^[56]. Zhang et al.^[57] reported that inoculation with endophytic bacterial strains effectively increases the abundance of PAH catabolic genes, thereby reducing PAH concentrations in vegetated soils and plants. In bioremediation processes, microorganisms mineralize organic contaminants to end products such as carbon dioxide and water, or to metabolic intermediates that are used as primary substrates for cell growth. For example, *Candidatus Methanoperedens* utilized methane as the sole carbon source to degrade methyl orange via direct interspecies electron transfer or the syntrophy pathway^[58]. The bioremediation of organic waste through microbial inoculants mainly depend on microbial specific enzymatic systems, which can assimilate, adsorb and biodegrade organic wastes in soil^[59]. Liu et al.^[59] demonstrated that the degradation rate of PAHs positively correlates with soil laccase activity. Notably, the adsorption of organic pollutants by microbial aggregates, attributed to hydrophobic regions in EPS, may contribute to the removal of organic pollutants^[53,60]. The primary mechanism for the removal of Microcystin-RR from aquatic solutions has been reported to be biosorption by microorganisms and microbial aggregates^[60].

2.4 Restoring degraded soils

Degraded soils have been abandoned worldwide due to both geogenic factors and anthropogenic factors, particularly in high- and middle-income countries^[61]. For example, one-third of the grasslands on the Qinghai-Tibet Plateau have become degraded under the interference of regional and persistent natural destruction, including wind and water erosion, freezing, and anthropogenic activities, such as overgrazing and unsuitable reclamation^[62]. Microbial inoculants can be used to restore abandoned lands because of their positive effects on plant growth and soil nutrients^[6]. Also, it is crucial to recognize the positive impact of microbial inoculants on the recovery of microbial community structure and function in abandoned soil. Li et al.^[63] conducted a 4-year field experiment at an abandoned mining site and examined the changes in microbial characteristics, soil nutrients, enzyme activities and functional genes to investigate the efficacy of mineral-solubilizing microbial inoculants in restoring derelict mine ecosystems. The study concluded that the application of mineral-solubilizing microbial inoculant significantly enhanced soil multifunctionality, including soil nutrients and enzyme activities, while decreasing microbial network complexity but increasing stability.

3 Nano-fertilizer for enhanced agricultural productivity

3.1 Nanomaterials for soil improvement

The NMs have emerged as promising tools for soil improvement, providing innovative solutions to enhance soil fertility, nutrient availability, and overall agricultural productivity^[64,65]. Due to their nanoscale size, these materials exhibit unique physical and chemical properties that make them particularly effective in addressing various soil-related challenges^[11]. The increased surface area and improved solubility of NMs facilitate better nutrient absorption by crop roots, leading to enhanced growth and yield. Additionally, NMs contribute to improving soil structure by promoting better aggregation of soil particles, which enhances porosity and aeration^[66]. They also improve water retention in soil, reducing water runoff and evaporation, thereby making water more available to plants. These properties make NMs valuable for sustainable agricultural practices, helping to address issues related to soil degradation and poor nutrient availability.

3.2 Nano-fertilizers

Nano-fertilizers might have the potential to revolutionize agriculture and help to meet the growing food demand for future generations^[65]. It offers innovative solutions to boost crop quantity and quality, particularly through fertilizer application and genetic improvement^[8]. A key advantage of nano-fertilizers over traditional fertilizers is their ability to release nutrients gradually over time due to their high surface area and nanoscale particle size, which can efficiently penetrate plant pores and improve nutrient use efficiency^[60]. For instance, the enhanced bioavailability of nutrients leads to improved root system development, increased leaf surface area and higher biomass production. These physiological and morphological improvements contribute to a substantial increase in crop yields and overall plant health. NM-based slow releasing fertilizer enhances nutrient bioavailability and absorption by crops^[67]. Zeolite-based nano-fertilizers can gradually release nutrients to crops, improving nutrient availability throughout the growing season and reducing losses from volatilization, leaching, denitrification, and fixation^[68]. Also, nano-fertilizers have been shown to reduce nutrient leaching, minimize environmental pollution, and improve soil fertility^[69]. A study by Chhowalla^[70] found that hydroxyapatite-urea nanohybrids released urea 12 times slower than urea fertilizer. Additionally, the incorporation of metal-based engineered NMs such as Cu, Fe, and Zn into nano-

fertilizers addresses micronutrient deficiencies in soil^[71] promoting healthier and more resilient crops. De Souza-Torres et al.^[72] demonstrated that Fe₃O₄ NPs, significantly enhances biological nitrogen fixation, leading to improved soil nitrogen levels and better crop performance. According to Kumar et al.^[73] nano-fertilizers can increase crop yields by up to 50% while using 50% less nitrogen than mineral fertilizers. Existing research on nanotechnology-based crop fertilizer application encompasses wide range of NMs, with a special focus on metal-based NMs comprising Cu, Fe, and Zn as micronutrients^[11,74]. Also, molybdenum disulfide NMs have shown great potential for enhancing biological nitrogen fixation and soybean growth, with a 30% increase in yield compared to the standard molybdenum fertilizer^[75]. Apart from their characteristics of gradual nutrient release, nano-fertilizers can be tailored to release nutrients selectively under various conditions, such as in the presence of water or at specific pH or temperature levels^[76]. Researchers assess the function of nano-fertilizers by examining various parameters, including morphological aspects such as plant growth, leaf surface area, root system size, and wet and dry matter production^[74,77], physiological^[78], biochemical^[60], and changes at molecular level^[77].

3.3 Impact on soil microbial communities

Soil microbes are crucial for sustaining the fertility and productivity of the soil^[79]. Nanoparticle treatments have the potential to substantially modify the soil microbiome, affecting the abundance and diversity of microbes. This, in turn, can influence crucial microbial processes such as mineralization, nitrogen fixation, and activities that promote plant growth^[8,77]. In addition, nitrogen and carbon cycles are often positively affected by nano-fertilizers. The stabilization of NPs in soil by natural organic matter can modify their surface chemistry, potentially affecting microorganisms and plants^[64]. Also, there is notable variability in the responses of plants and their associated rhizosphere bacteria to NPs. The overall influence of NPs on rhizosphere microbiome is contingent upon factors such as the properties and concentration of the NPs, the types of microbes in the environment and prevailing soil conditions^[80]. Although certain studies indicate that NPs may have detrimental effects on rhizosphere microbiome, NPs can actually stimulate it. This implies the potential to leverage these beneficial root-microbe relationships^[7,81]. The presence of NPs in the plant rhizosphere establishes a distinctive environment conducive to the interaction between plants and NPs^[82]. While silver NPs had a differential impact on rhizosphere of maize and overall microbial community structure, with a more notable alteration in bacterial community compared to the fungal community^[83]. Despite changes to rhizosphere

microbial community, maize growth was positively affected, suggesting either the suppression of pathogenic bacteria or an expansion in valuable bacteria^[83]. Cerium dioxide NPs at concentrations of 300–2000 mg·L⁻¹ significantly improved strawberry plant growth, however reduced the diversity of the rhizosphere microbial community^[84]. The change in microbial diversity corresponded with an increased prevalence of microbes that promoting plant growth, affecting nutrient cycling, and providing protection against diseases^[83].

It has been reported that the some species in the phylum *Bacteroidota* have silver resistance genes, enabling them to withstand the presence of silver NPs and, in fact, thrive in their presence^[8]. The disintegration of silver-sensitive microbial cells liberates a readily accessible pool of carbon sources, which *Bacteroidota* efficiently metabolize, fostering their proliferation and enhancing their relative abundance within the microbial community^[85]. Application of 1 mg·g⁻¹ iron(III)-silver NMs decreased the abundance of *Verrucomicrobia* and *Chloroflexi*, likely due to their lack of an outer membrane and high sensitivity to silver^[86]. Further, Lin et al.^[87] illustrated that green synthesized iron oxide NPs improved the composition of the soil microflora in cadmium-contaminated soil. The NMs have a neutral to positive impact on native microflora and biodiversity at low concentrations.

3.4 Nanomaterials for disease management

Plant pathogens, ranging from simple viroid to complex organisms like bacteria, fungi, nematodes, and oomycetes, cause a variety of plant diseases, resulting in significant agricultural losses worldwide. NPs not only act as nutrient carriers for plants but also demonstrate effectiveness against a broad spectrum of pathogenic microorganisms^[74]. Their application, therefore, holds the potential to serve a dual purpose by bolstering agricultural productivity through enhanced disease resistance. Rexlin et al.^[88] addressed the challenge of declining crop production by using biocompatible, relatively non-toxic and biodegradable zinc oxide NPs to improve both quality and productivity of cluster bean seeds and pods. Applying zinc oxide NPs effectively addressed zinc deficiency in plants and showed remarkable and diverse antibacterial and antifungal properties, likely due to the release of reactive oxygen species (ROS) and zinc ions, which deactivate bacterial cell walls and exhibit strong antimicrobial activity^[89]. Additionally, research on carrots has revealed that silica enhances plant development and its resistance^[90]. Silica NPs interact with cell wall to form an additional cuticle layer, which acts as a barrier to inhibit the entry of pathogens into plant cells and contribute to disease resistance in various

crops^[91]. El-Shetehy et al.^[92] demonstrated that silica NPs induced resistance in *Arabidopsis* in a dose-dependent manner, while copper NPs effectively treated *Fusarium* wilt and improved tomato plant growth. Copper NPs served as a micronutrient source in copper-deficient soils, primarily enhancing plant growth and elevating total chlorophyll levels^[93]. Nano-Cu and -Si are widely used in the contemporary management of plant diseases. Similarly, the presence of 30 nm silica NPs reduced the growth of the pathogen *Fusarium oxysporum* in tomato stems, highlighting the potential of silica NPs as a contributor in a sustainable crop protection strategy^[94]. Abdelkhalek and Al-Askar^[89] used an aqueous leaf extract of *Mentha spicata* to biologically synthesize zinc oxide NPs and then evaluated their antiviral efficacy against the tobacco mosaic virus. Recent research has demonstrated that diverse NPs can be effectively used to manage plant diseases, by reducing the incidence of diseases they can improve overall plant health^[81]. The NMs have broad-spectrum antimicrobial properties, making them inherently suitable for direct use as pesticides for plants and edible crops to manage pests and disease. Various NMs are also used as nano-carriers to deliver pesticides precisely to the intended site of action^[95].

4 Role of nanotechnology in mitigating abiotic stress

In addition to impacting growth and development, NPs can alleviate harmful effects of various significant abiotic stresses affecting plants. Plant productivity and yield are severely limited by ever-increasing abiotic conditions such as drought, salt, waterlogging, heat stress, and heavy-metal toxicity^[96]. Abiotic stresses inevitably induce production of ROS in response to restricted oxygen supply within plant cells^[96]. Although plants acquire enzymatic machinery to mitigate oxidative stresses from environment, severe stress can overwhelm their defense mechanisms, leading to significant physiological and molecular consequences^[97]. The NPs alleviate abiotic stresses by activating specific genes, accumulating osmolytes, enhancing phytonutrient levels and producing photopigments^[98]. Their particularly small size gives them unique properties that distinguish them from their bulk counterparts and open new possibilities in various fields of application^[99].

4.1 Nanomaterials for drought mitigation

Drought stress in plants causes several changes in growth traits and biochemical reactions, including stunted growth and

slowed photosynthesis^[100]. The application of phyto-genic NPs is an emerging strategy to mitigate these adverse effects. Available reports suggest that NPs enhance drought resistance in a variety of crops, including wheat^[101], eggplant^[102], strawberries^[103], and barley^[104]. The NPs increase photosynthetic pigment and crucial compound levels, such as proline and carbohydrates, in strawberry leaves under drought stress^[103]. Excessive production of malondialdehyde (MDA) under drought stress causes oxidative damage in plants^[103]. The application of NPs to drought-stressed plants elevates levels of enzymatic antioxidants and reduces MDA content. The NPs enhance drought resilience of hawthorn by increasing photosynthetic rates and stomatal conductance^[105]. Similarly, applying selenium NPs (30 mg·L⁻¹) to wheat under drought conditions promotes plant growth while decreasing ionic leakage and lipid peroxidation, mitigating the toxicity of drought-induced cellular damage^[106]. By regulating ion balance and ROS metabolism, silica NPs reduce cellular damage and promote photosynthesis in stressed plants^[107]. Silica NPs promoted post-drought plant recovery in barley by altering morphophysiological properties. Chitosan NPs improved relative water content, photosynthetic rate, CAT and SOD activities, as well as yield and biomass in drought-stressed wheat^[108].

4.2 Nanomaterials for heat stress alleviation

Heat stress occurs when plants are exposed to elevated temperatures exceeding their optimal growth range for durations ranging from minutes to hours, significantly impacting plant growth and development^[109]. The ROS, particularly hydrogen peroxide, are believed to be crucial for signaling in plant response to heat stress^[110]. Regulating levels of ROS is essential for effective signaling and reducing heat stress damage. While heat stress can alter plants at all stages of development, it has the most significant impact during preliminary establishment, flowering, gametogenesis and floral meristem growth^[111]. The application of biocompatible NPs has demonstrated high efficacy in enhancing the survival of wheat plants under heat stress conditions^[111].

4.3 Nanomaterials for cold stress mitigation

Plants frequently encounter two distinct types of low-temperature stress, namely chilling and freezing. The optimal temperature range for plant growth and development is influenced by various factors, including the specific plant species and its individual tolerance level. In general, chilling temperatures range from 0 to 15 °C. Additional variables, such as ambient air temperature and wind velocity throughout the

period of exposure, also exert an impact on chilling temperatures. In contrast to their ability to withstand cold temperatures, plants have to enduring freezing temperatures, which fall below 0 °C^[112]. Low and non-freezing temperatures can harm or kill crops, affecting their productivity, survival and ecological distribution^[113]. Nanoparticle-mediated approaches have been used to mitigate cold stress through various mechanisms. For example, titanium dioxide NPs mitigate the harmful effects of cold stress by enhancing antioxidant enzyme activities, reducing oxidative damage, and increasing glycyrrhizin content in licorice plants^[114]. Chitosan NPs mitigate ROS levels and promote the accumulation of osmoprotectants, such as proline and soluble sugars, which help stabilize cellular structures and maintain osmotic balance in banana plants under cold stress^[115]. Additionally, the foliar application of zinc oxide NPs alleviates chilling stress in rice plants by modulating the antioxidative system, enhancing the activity of enzymes like superoxide dismutase and catalase, and upregulating transcription factors related to the chilling response^[91]. Similarly, silica NPs enhance the photosynthetic capacity of sugarcane plants experiencing chilling stress by improving chlorophyll content and maintaining the integrity of the photosynthetic apparatus^[116].

4.4 Nanomaterials for salinity stress reduction

In the field of agriculture, NPs have been recognized as an effective way to improve crop productivity under salt stress condition^[98,117] (Fig. 1). Several studies have demonstrated that NPs enhance the ability of different plant species to tolerate high levels of saline^[98,99,102]. Additionally, zinc oxide NPs enhance the salinity tolerance of *Oryza sativa* by preserving cell membrane stability. This is achieved through the reduction of lipid peroxidation and the maintenance of membrane integrity, preventing the loss of essential ions and cellular components under salt stress^[118]. Iron oxide NPs have been shown to increase the biomass, antioxidant concentrations, and photosynthetic pigments in wheat under salinity stress. This improvement in photosynthetic efficiency leads to better energy capture and utilization, supporting plant growth and productivity even in saline conditions^[117]. The NPs, including Cu, K₂SO₄, Se, SiO₂, TiO₂, and ZnO, significantly enhance the activity of several antioxidant enzymes such as APX, CAT, GPX, GR, POD, POX, and SOD. This enhancement mitigates oxidative stress by scavenging reactive oxygen species, thereby protecting cellular structures and metabolic functions from oxidative damage caused by

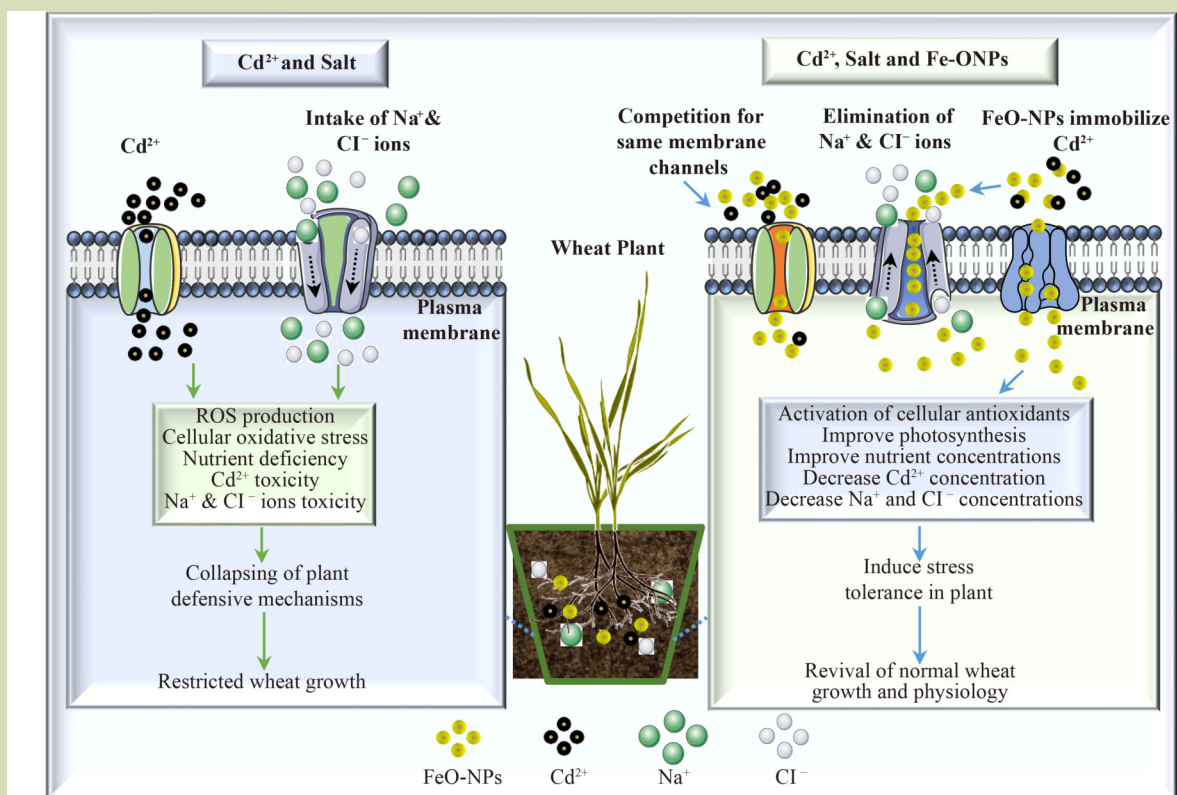


Fig. 1 Functioning of biogenic nanomaterials on alleviating soil salinity and heavy metal stresses. Reproduced from Manzoor et al.^[117], with permission from Elsevier, Copyright 2021.

excessive salt stress^[119]. This ability to enhance antioxidant enzyme activity allows NPs to alleviate complications of oxidative stress induced by salt stress.

4.5 Nanoremediation of heavy metals

Soil contamination by various pollutants stands as one of the most critical environmental challenges, adversely impacting both terrestrial and aquatic ecosystems. Heavy-metal pollution is perturbing the environment and posing severe health risks to human beings^[120]. Exposure to cadmium, lead, arsenic, and fluoride through contaminated food and drinking water can cause significant health problems, including skin, lung, kidney, and brain damage^[121]. Nanotechnology offers significant benefits for sustainable agriculture by enhancing nutrient use, mitigating climate change impacts and remediating heavy metals in soil^[122]. Researchers have reported that NPs can immobilize heavy metals in soil^[123]. The NPs can immobilize heavy metals, reducing their mobility and bioavailability, thus benefiting soil microbes and plants^[121,123]. Applying NPs reduces the mobility and bioavailability of metal contaminants in the soil. For example, selenium and iron(III) oxide NPs stabilize Cd, limiting its movement and biological activity in

plants^[124]. The NPs form complexes with heavy metals that become immobile after absorption, preventing heavy metals from moving within plants and reducing their biological activity^[98]. Additionally, NPs enhance apoplastic barriers in roots, controlling heavy-metal uptake^[125]. This results in improved plant growth and yield under metal stress conditions due to the stress-alleviating role of NPs^[126,127], as shown in Fig. 2. Reactive NMs can also detoxify and transform specific pollutants^[76].

5 Nanotechnology for enhancing seed germination, growth and crop productivity

Nanotechnology has recently gained increasing prominence in enhancing agricultural productivity. The NMs have demonstrated efficacy in improving seed germination, leading to enhanced plant growth and fruiting rates. Numerous studies have consistently corroborated the high efficacy of NMs for both germination and plant growth^[98,124]. Montanha et al.^[128] found that nanocoating soybean seed surfaces with zinc (as

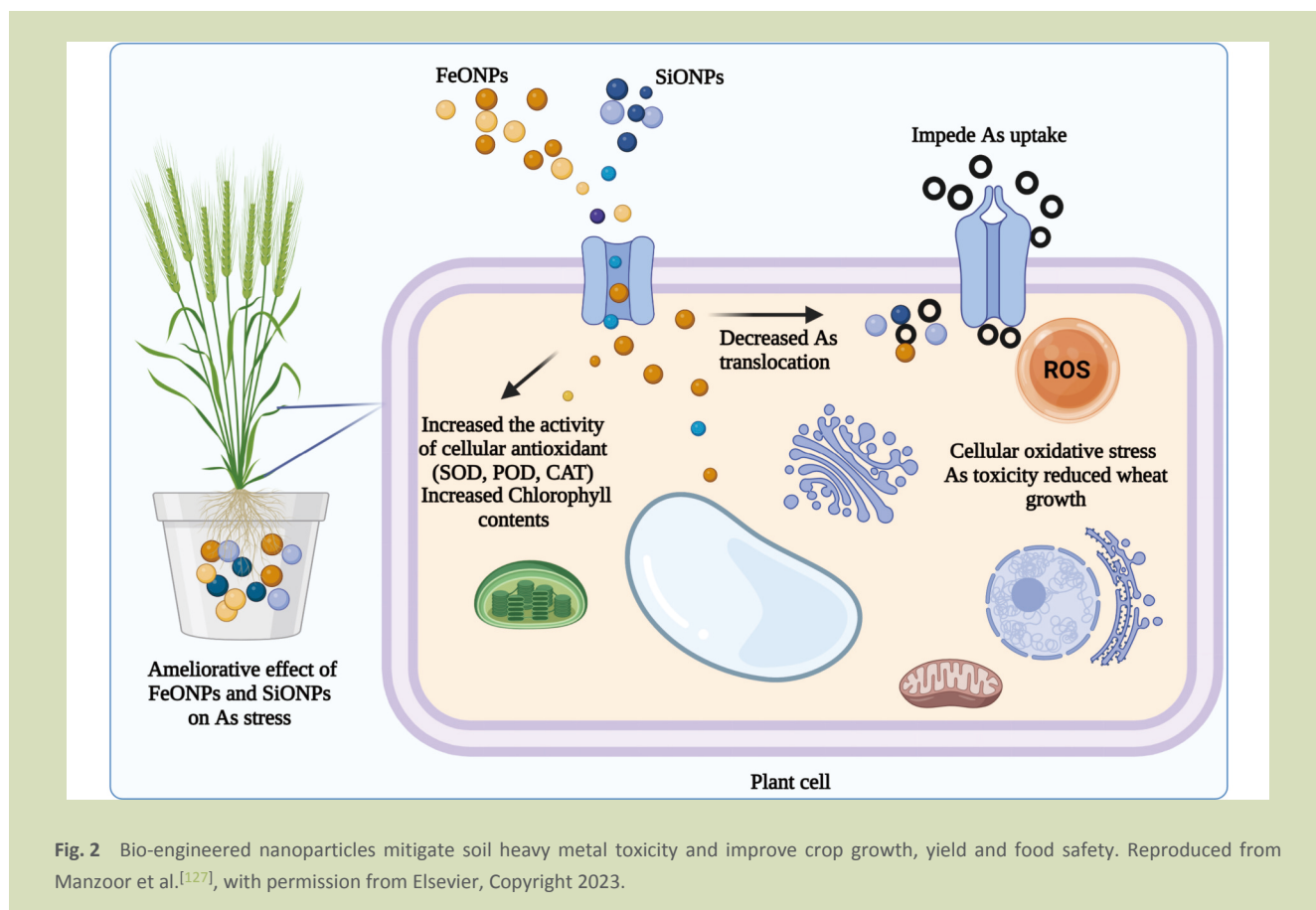


Fig. 2 Bio-engineered nanoparticles mitigate soil heavy metal toxicity and improve crop growth, yield and food safety. Reproduced from Manzoor et al.^[127], with permission from Elsevier, Copyright 2023.

ZnSO₄ and ZnO) improved germination. Some NPs can stimulate seed metabolism, seedling vigor and overall plant growth by modulating cellular signaling pathways^[65,90]. For example, graphene and its derivatives can serve as efficient water transporters in the soil, accelerating water absorption by seeds, promoting seed germination, and stimulating the growth and development of plants^[129]. In another study, Ag NPs were absorbed by roots and localized in the cell wall and intercellular spaces. Their presence influenced cell division, thereby regulating root elongation^[124]. Zinc NPs promote germination in various plants, including beans^[130], chili^[131], maize^[132], and wheat^[133].

Foliar application of silver and zinc NPs enhanced the growth and productivity of mung beans, increasing the number of branches per plant, chlorophyll content, grain yield and number of pods per plant^[101]. Foliar spraying of K₂SiO₃ on maize leaves improved water use efficiency and yield under low irrigation conditions, while also enhancing grain protein and oil contents^[134]. Applying Si fertilizer increased concentrations of nitrogen, phosphorus, potassium, calcium, iron, manganese, copper and zinc in sugarcane plants. Sugarcane parameters correlated positively with Si levels, with height, stalk diameter and dry leaf biomass being 50%, 58%, and 71% higher, respectively, in treated plants than in controls^[135]. The impact of NPs on crop growth under various stress conditions is summarized in Table 2.

Green nanotechnology holds the potential to enhance crop yields through multiple mechanisms, such as developing crops resistant to extreme temperatures, formulating targeted insecticides for specific pests, addressing global warming issues, and creating nanotubes to retain soil moisture^[142]. Both iron(III) oxide and iron(II) hydroxide NPs can be used as

nano-fertilizers to enhance iron nutrition^[143]. The impact of NPs on biological systems is largely determined by their physicochemical properties, including size, zeta potential, and concentration^[77,98].

6 Biochar as an additive toward improving soil quality and functionality

6.1 Biochar as a microbial carrier

Biochar significantly influence the microbial community diversity and composition within charosphere environment^[12], as illustrated in Fig. 3. Specific bacteria immobilized on biochar have demonstrated excellent capabilities in adsorbing organic compounds such as nonylphenol^[144] and phenanthrene^[145], as well as heavy metals^[146]. Notably, the removal efficiencies of these contaminants appear to be higher when using biochar-immobilized bacteria compared to either biochar or bacteria alone. Liu et al.^[146] demonstrated that the combined application of biochar and manganese-oxidizing bacteria was effective for soil contaminated with Pb and As, while also showing greater potential for addressing Pb and Cd pollution in water. Numerous studies have established biochar as a viable carrier for beneficial bacteria, demonstrating its potential to sustain the viability of these microorganisms over extended periods. Thies and Rillig^[147] observed that bacteria attach to biochar particles through multiple methods, including flocculation, adsorption on surfaces and covalent bonding. They noted that the high porosity, sorption capacity and water holding capacity of biochar created suitable habitats for microorganisms, promoting these activities. A study by Husna

Table 2 Impact of nanoparticles on plant growth and stress resistance

Nanoparticle	Crop	Stress	Beneficial impact	Source
FeO	Wheat	Salinity	Mitigate Cd and salt stresses	[117]
IO	Rice	Drought and heavy metal	Improve the nutrient acquisition by reducing Cd stress	[136]
SiO, FeO	Wheat	Heavy metal	Stimulate antioxidant enzymes and reduce the ROS	[127]
SiO	Wheat	Heavy metal	Mitigate metal stress and maintain cellular structure	[126]
Si	Rapeseed	Heavy metal	Changed the expressions of antioxidant defense and stress related genes	[137]
Ag	Rice	Disease management	Increase plant biomass reduce the ROS	[138]
Chitosan Fe	Rice	Disease management	Improve transcript level of defense-related genes	[139]
Ag	Wheat	Cold and heat stress	Increases relative water content, reduce proline and sugar level, adjust osmotic level and ROS detoxification	[140]
Zn, Fe	Wheat	Cold and heat stress	Enhances yield, antioxidant enzymes activity, and decreases lipid peroxidation	[141]

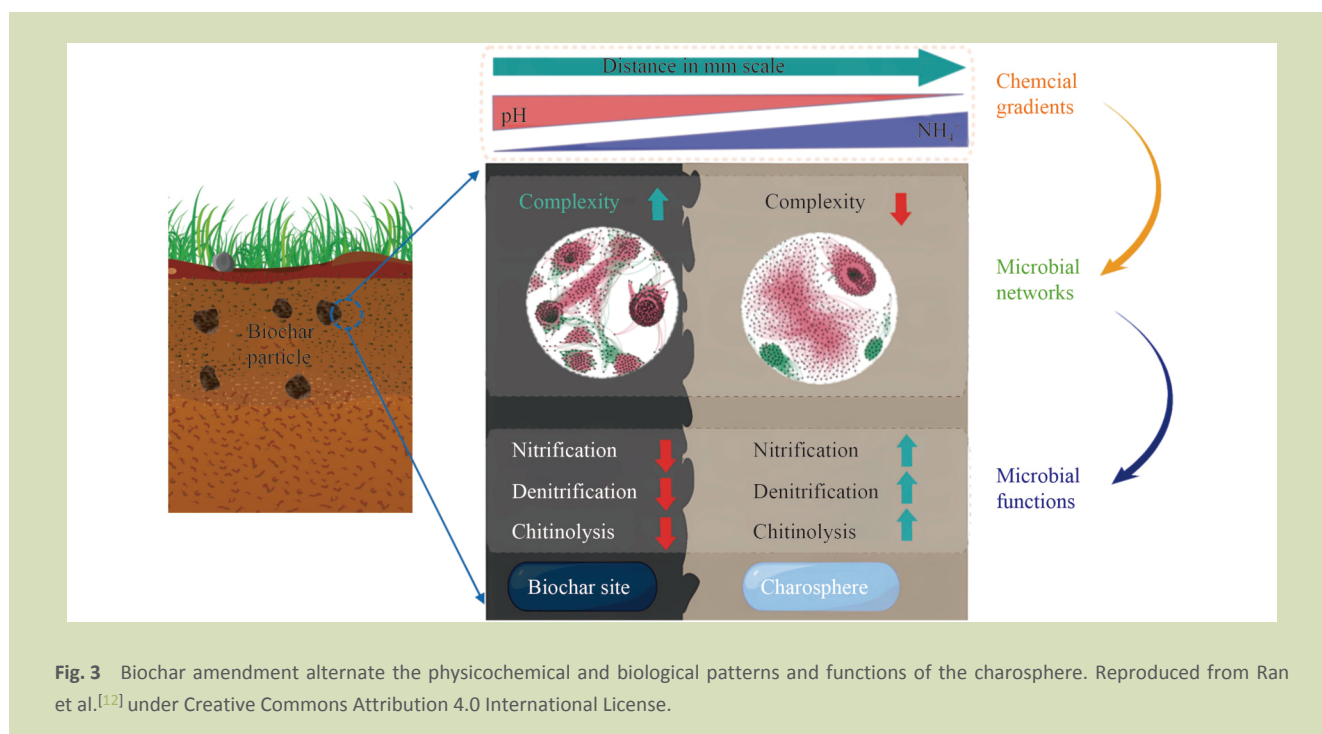


Fig. 3 Biochar amendment alternate the physicochemical and biological patterns and functions of the charosphere. Reproduced from Ran et al.^[142] under Creative Commons Attribution 4.0 International License.

et al.^[148] focused on agricultural waste materials as biochar, demonstrating that certain biochars maintained microbial viability for up to 6 months. For instance, coconut shell biochar exhibited high phosphate-solubilizing microorganism viability. In another study, Xiang et al.^[149] compared pine bark-derived biochar and sewage sludge-derived biochar with standard carriers like perlite and poultry litter. They discovered that pine bark-derived biochar extended the shelf life of bacteria by up to a year. These findings highlight the promise of biochar as a microbial carrier, offering a cost-effective, eco-friendly solution to improving crop yield and soil quality. As research progresses, our understanding of the potential applications for biochar continues to expand. The increasing evidence suggests that this versatile chemical has substantial potential for addressing current challenges in agricultural and ecological oversight. A global meta-analysis revealed that biochar could increase soil microbial biomass and affect the activities of extracellular enzymes, such as those involved in N cycling (urease) and P cycling (alkaline phosphatase), and intracellular enzyme, such as dehydrogenase, with no significant negative effects on any of the enzymes analyzed in this investigation^[150]. Similarly, Yan et al.^[151], demonstrated that biochar-based fertilizers (combined with compost or NPK fertilizers) improved soil properties and contributed to the recovery of degraded karst soils. This was achieved by stimulating microbial activities and growth and enhancing soil nutrient (N, P, and K) availability. These findings further emphasize the multifaceted benefits of biochar in soil amendment and microbial ecology^[150,151]. Recent research has also investigated

the use of biochar as a carrier material for microbial inoculants to promote early colonization of the rhizosphere with microbial incubations^[32,152]. Compared to direct soil application of *Enterobacter cloacae*, using pinewood biochar as a carrier resulted in increased survival of the inoculum.

Also, biochar applied in conjunction with microbial inoculants has been reported to provide, in most cases, apparent benefits in the form of increased yields, improved soil properties, reduced greenhouse gas emissions and improved nutrient circulation^[150]. The study of Rafique et al.^[23] investigated the effects of biochar, P fertilizer, PSB, and AMF on maize growth, and found that the addition of biochar significantly improved nutrient absorption and plant biomass production when combined with P fertilizer, AMF, and PSB. Also, the combined use of biochar and microbial inoculants to control plant diseases has been well-reported in the literature^[106]. Combined amendment of biochar and *Bacillus* synthetic community effectively controlled soilborne disease and improved plant physiological parameters through remodeling the plant and rhizosphere microbiome^[153].

6.2 Biochar improve the nutrient cycling in soil ecosystems

Biochar serves as an excellent carrier of essential nutrients such as N, P, and K, attributing to the large load ability of the porous structure and strong adsorption ability toward nitrate,

ammonium and phosphate ions. Biochar amendments enhance soil porosity, water retention capacity, nitrogen retention time and microbial activity. Research has shown that soil organic carbon can increase by an average of 39% with the application of appropriate biochar types^[154,155]. A long-term microcosm experiment demonstrated that the interaction between biochar and plants led to increased fungal biomass, soil macroaggregate formation, and iron-bound non-biochar carbon content^[156]. Experiments and meta-analysis conducted on different types of soils and biochars consistently indicate that the applications of biochar help to improve the soil carbon sequestration and reduce greenhouse gas emissions^[154,156,157]. While the effects of biochar on N cycling depend on both biochar characteristics and soil properties, meta-analyses suggest that biochar amendments can significantly alter nitrogen dynamics^[157]. Field and laboratory experiments showed that biochar application significantly enhances soil ammonium and nitrate content, N mineralization, N₂ fixation, and plant N uptake, while inhibiting nitrate leaching and gaseous nitrogen emissions^[158]. These effects contribute to improved crop productivity. Also, biochar can effectively be used to enhance soil properties and crop yields (Table 3).

Biochar can also act as electron mediators (donor, shuttle, and conductor) in the redox reactions in soils, including denitrification, dissimilatory nitrate reduction to ammonium, ammonia oxidation, and iron oxidation/reduction^[170]. The

function of biochar as the electron shuttle is proved to decrease the N₂O emission and N₂O/(N₂O + N₂) emission ratio by controlling the electrochemical properties of biochar^[171], and enhance anaerobic ammonium oxidation coupled to iron reduction and long-distance extracellular electron transport^[172,173]. The Fe(III) reduction in clay minerals was found to be affected by the biochar concentration due to its electron shuttling and buffering capacity^[174]. Villada et al.^[175] demonstrated that biochar-based fertilizers, created by impregnating biochars from various agricultural residues with biogas slurry, show promising results in controlled nutrient release and enhanced plant nutrition. This approach offers a sustainable method for NPK recovery and fertilizer production in agriculture. Biochar application generally increases plant-available P in agricultural soils. A meta-analysis of 108 studies found that biochar addition increased soil P availability by a factor of 4.6 on average^[176]. Ye et al.^[177] found that biochar prepared under CO₂ or H₂O (gaseous state) atmosphere contained more surface groups for K adsorption, and active groups on biochar surface had enhanced N and P adsorption^[178]. Also, biochar modified with nutrient elements, such as nitrogen and phosphorous, or biochar-based controlled-release fertilizer is used to improve the microbial community function and food production^[179]. The combined adsorption and long-distance electron transport capabilities of biochar enhance its potential applications in the agricultural industry.

Table 3 Impact of biochar on soil properties and crop productivity

Biochar Feedstock	Pyrolysis (°C)	Application rate	Result	Source
Maize stalks	450	0, 10, 20, and 40 t·ha ⁻¹	Improve soil quality and crop productivity	[159]
Wood sawdust maize stalk	500	5, 10, and 19 t·ha ⁻¹	Enhance soil fertility by mitigating salt-affected soils	[160]
Sugarcane filter cake, rice husk	350	0.25%, 0.50%, and 0.50% (w/w)	Improve soil fertility status and nutrients availability	[161]
Maize straw	400	0, 10, 30, and 50 t·ha ⁻¹	BC application affected, AMF, and the ratio of AMF/saprotrophic fungi	[162]
Manures, wood and herbaceous materials	≤ 500 >500	1–39, 40–80, > 80 t·ha ⁻¹	Improve CEC and organic carbon, reduced bulk densities, increased porosity	[163]
Wheat straw	500	0, 3%, and 5% (w/w)	Improved plant height, thousand grain weight, and biological yield.	[164]
Maize straw	350	0, 0.5%, 1%, 2%, 2.5%, 5%, and 10% (w/w)	Improved soil WHC, reduced soil Na ⁺ content and SAR, enhanced soil fertility and enzyme activity	[165]
Sunflower stalks	400	15 t·ha ⁻¹	Improved soil water content, microbial biomass carbon, basal respiration, dissolved organic carbon, available nitrogen, and phosphorus	[166]
Paper fiber sludge and grain husks	550	0, 10, and 20 t·ha ⁻¹	Improved soil sorption properties, soil organic carbon, and crop yield	[167]
Cassava straw	200–400	0, 20, 40, and 60 t·ha ⁻¹	Improved photosynthetic rate, grain yield, N uptake, amylose, and protein content in biochar treated pots	[168]
Maize straw	600	0, 5, 10, 15, 20, 25, and 30 t·ha ⁻¹	Enhanced contents of CEC, organic matter, and nutrients of 0–20 and 20–40 cm	[169]

7 Challenges and perspectives

7.1 Difficulties with microbial inoculants application

Despite decades of research into soil microbial inoculants, significant obstacles remain to their widespread application. The introduction of microbial cells into soil aims to promote rapid colonization of the host rhizosphere. However, this approach faces several limitations. Effective inoculants, selected for their strong competitive and root-colonizing abilities, can substantially impact plant health^[180]. Plants and soil microbiomes possess sophisticated communication networks^[108]. The introduction of microbial inoculants could disturb the coevolved plant-microbe interactions and the equilibrium of soil microbial communities^[7,109]. These inoculant-induced changes can result from direct trophic competition or from antagonistic or synergistic interactions between introduced and resident microbes. Notably, one of the most critical factors to consider when introducing microbial inoculants is their capacity to disperse within the recipient habitat, as this will influence their potential access to locations and resources following application^[111].

7.2 Mass production, application, and health risk of nano-fertilizer

Nano-fertilizers have substantial potential for enhancing agricultural productivity and sustainability by improving nutrient delivery to plants^[181] (Fig. 4). However, their production, application and potential health risks also present significant challenges and complexities. The production of nano-fertilizers requires precise control over particle size, composition and surface properties. Achieving this level of precision can be technically demanding and expensive. While laboratory-scale production may yield promising results, scaling up the production process to meet agricultural demand while maintaining consistent quality is challenging. Some nano-fertilizer production methods rely on rare or expensive materials, energy-intensive processes or complex synthesis techniques, which can limit scalability and increase production costs. The environmental impact of nano-fertilizer production, including energy consumption, waste generation and potential pollution from byproducts, requires careful consideration. Ensuring uniform distribution of nano-fertilizers in soil or on plants is crucial for their effectiveness. Achieving this uniform dispersion can be challenging, especially in large-scale agricultural settings. Nano-fertilizers must integrate seamlessly with existing agricultural practices, including machinery, irrigation systems, and crop management techniques. Nano-

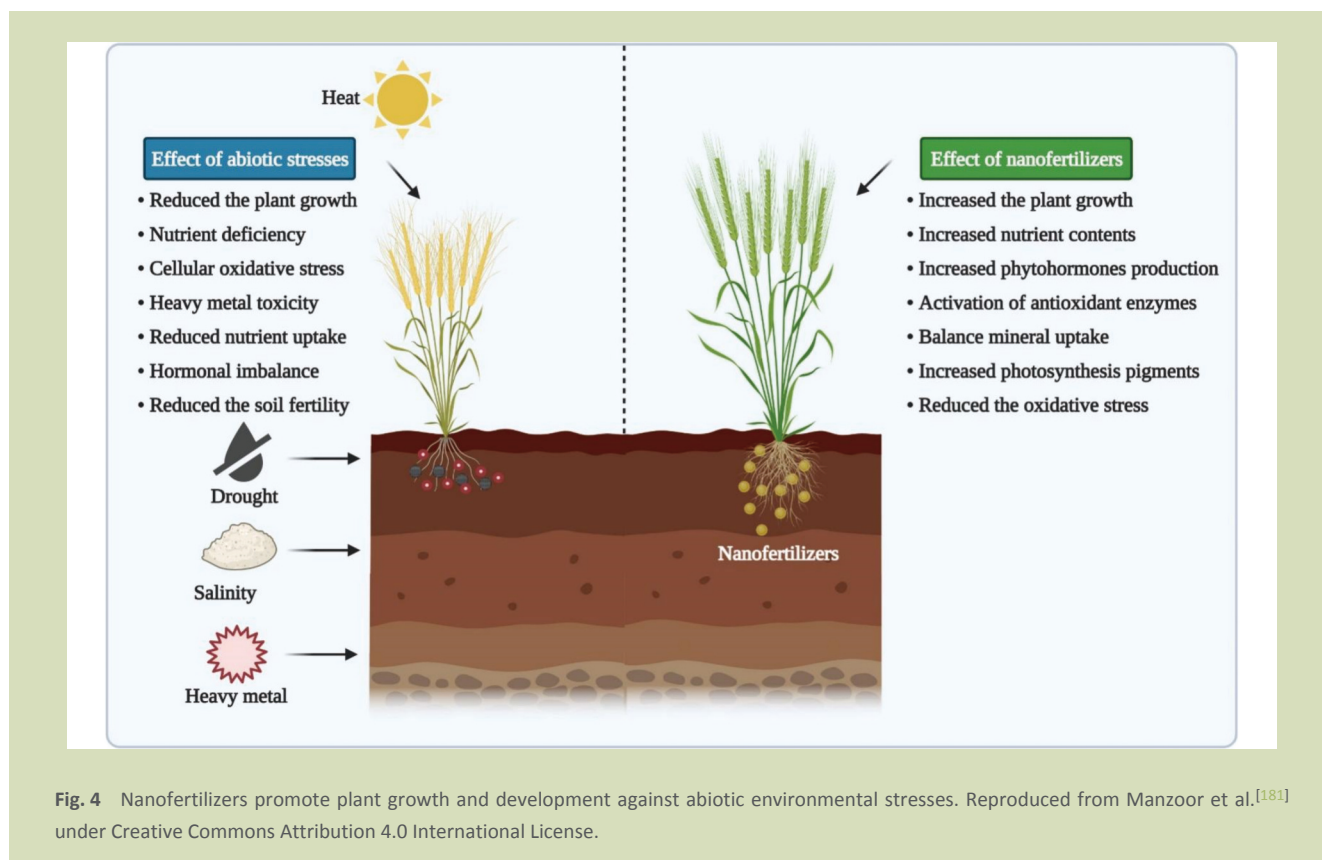


Fig. 4 Nanofertilizers promote plant growth and development against abiotic environmental stresses. Reproduced from Manzoor et al.^[181] under Creative Commons Attribution 4.0 International License.

fertilizers must integrate seamlessly with existing agricultural practices, including machinery, irrigation systems, and crop management techniques. Additionally, they should maintain stability over time and under various environmental conditions to provide sustained nutrient release and prevent leaching or degradation. Also, NPs from nano-fertilizers could potentially enter water bodies, soil and the food chain, posing risks to ecosystems and human health through bioaccumulation and biomagnification. Current regulations may not adequately address the unique risks associated with nano-fertilizers, necessitating robust safety assessments and regulatory frameworks. While nano-fertilizers offer exciting possibilities for enhancing agricultural productivity and sustainability, addressing the challenges of production, application and health risks is essential to ensure their safe and effective implementation. Close collaboration between researchers, industry stakeholders, policymakers and regulatory bodies is crucial to overcome these challenges and realize the full potential of nano-fertilizers while safeguarding human health and the environment.

7.3 Effective application of biochar and its contribution to carbon neutrality

Biochar has substantial potential for mitigating climate change and advancing carbon neutrality. However, its widespread adoption faces several challenges that require careful consideration and further research. Large-scale production and

cost management remain major hurdles in the widespread adoption of biochar. There is a pressing need to develop efficient and environmentally-friendly pyrolysis technologies that can be scaled up economically. The economic feasibility of large-scale biochar production, including a comprehensive assessment of costs and benefits across various sectors, must be thoroughly evaluated. Despite these challenges, biochar has clear potential for addressing environmental issues. It has been shown to improve soil health, enhance microbial function, and increase food production. Importantly, biochar acts as a stable carbon sink, effectively reducing atmospheric CO₂ levels. This carbon sequestration potential makes biochar a valuable tool in mitigating greenhouse gas emissions and combating climate change.

Effective biochar application offers a multifaceted approach to achieving carbon neutrality by sequestering carbon, improving soil health and promoting sustainable agricultural practices. Integrating biochar into climate change mitigation requires collaboration among policymakers, researchers, farmers and industry stakeholders. Economic feasibility of large-scale biochar production, including costs and benefits for various sectors, must be assessed. Supportive policies and incentives are needed to promote biochar adoption. Further research and policy support are crucial for realizing the full potential of biochar in addressing global environmental challenges.

Acknowledgements

The authors acknowledge the financial supports of the National Natural Science Foundation of China (42102340, 42277298), the Pingduoduo-China Agricultural University Research Fund (PC2023B02007), the National Key Research and Development Project of China (2022YFD1500205), and the National High-end Foreign Experts Recruitment Plan (G2022108011L).

Declaration regarding the use of generative AI and AI-assisted technologies

During the preparation of this work, the authors utilized the Claude tool to enhance language quality and readability. Subsequent to its use, the authors conducted a thorough review and made necessary edits to the content, thereby accepting full responsibility for the entirety of the publication's content.

Compliance with ethics guidelines

Ying Liu, Natasha Manzoor, Miao Han, Kun Zhu, and Gang Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Strer M, Svoboda N, Herrmann A. Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany. *Environmental Sciences Europe*, 2018, **30**(1): 10
2. Mao H, Chen S J, Ying R Y, Fu Y. How crop insurance influences agrochemical input use: evidence from cotton

- farmers in China. *Australian Journal of Agricultural and Resource Economics*, 2023, **67**(2): 224–244
3. Santos M S, Nogueira M A, Hungria M. Microbial inoculants: reviewing the past, discussing the present and previewing an outstanding future for the use of beneficial bacteria in agriculture. *AMB Express*, 2019, **9**(1): 205
 4. Pandiyan A, Sarsan S, Guda Sri Durga G, Ravikumar H. Biofertilizers and biopesticides as microbial inoculants in integrated pest management for sustainable agriculture. In: Pratap Singh R, Manchanda G, Sarsan S, Kumar A, Panosyan H, eds. *Development in Application of Microbial Biotechnology*. New York: *Academic Press*, 2024, 485–518
 5. Ayilara M S, Adeleke B S, Akinola S A, Fayose C A, Adeyemi U T, Gbadegesin L A, Omole R K, Johnson R M, Uthman Q O, Babalola O O. Biopesticides as a promising alternative to synthetic pesticides: a case for microbial pesticides, phytopesticides, and nanobiopesticides. *Frontiers in Microbiology*, 2023, **14**: 1040901
 6. Alori E T, Dare M O, Babalola O O. Microbial inoculants for soil quality and plant health. In: Lichtfouse E, ed. *Sustainable Agriculture Reviews*. Springer International Publishing, 2017, 281–307
 7. Kumar A, Dubey A. Rhizosphere microbiome: engineering bacterial competitiveness for enhancing crop production. *Journal of Advanced Research*, 2020, **24**(2): 337–352
 8. 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**(Pt 2): 132107
 9. Naseem F, Zhi Y, Farrukh M A, Hussain F, Yin Z Y. Mesoporous ZnAl₂Si₁₀O₂₄ nanofertilizers enable high yield of *Oryza sativa* L. *Scientific Reports*, 2020, **10**(1): 10841
 10. Ahmed T, Noman M, Qi Y T, Xu S C, Yao Y L, Masood H A, Manzoor N, Rizwan M, Li B, Qi X J. Dynamic crosstalk between silicon nanomaterials and potentially toxic trace elements in plant–soil systems. *Ecotoxicology and Environmental Safety*, 2023, **264**: 115422
 11. Sohail M I, Waris A A, Ayub M A, Usman M, ur Rehman M Z, Sabir M, Faiz T. Environmental application of nanomaterials: a promise to sustainable future. In: Verma S K, Das A K, eds. *Comprehensive Analytical Chemistry*. Elsevier, 2019, 1–54
 12. Ran H Y, Wang Y, Wei K Y, Liu Y, Wang G, Zhu K. Spatial and temporal changes of charosphere hotspots with or without nitrogen additions. *Biochar*, 2023, **5**(1): 49
 13. Rajabi H, Hadi Mosleh M, Prakoso T, Ghaemi N, Mandal P, Lea-Langton A, Sedighi M. Competitive adsorption of multicomponent volatile organic compounds on biochar. *Chemosphere*, 2021, **283**: 131288
 14. Hesham A E L, Kaur T, Devi R, Kour D, Prasad S, Yadav N, Singh C, Singh J, Yadav A N. Current trends in microbial biotechnology for agricultural sustainability: conclusion and future challenges. In: Yadav AN, Singh J, Singh C, Yadav N, eds. *Current Trends in Microbial Biotechnology for Sustainable Agriculture*. *Environmental and Microbial Biotechnology*, 2021, 555–572
 15. Shahwar D, Mushtaq Z, Mushtaq H, Alqarawi A A, Park Y, Alshahrani T S, Faizan S. Role of microbial inoculants as bio fertilizers for improving crop productivity: a review. *Heliyon*, 2023, **9**(6): e16134
 16. Xing J P, Cao X C, Zhang M C, Wei X, Zhang J, Wan X Y. Plant nitrogen availability and crosstalk with phytohormones signalling and their biotechnology breeding application in crops. *Plant Biotechnology Journal*, 2023, **21**(7): 1320–1342
 17. Sheng Y Z, Baars O, Guo D Y, Whitham J, Srivastava S, Dong H L. Mineral-bound trace metals as cofactors for anaerobic biological nitrogen fixation. *Environmental Science & Technology*, 2023, **57**(18): 7206–7216
 18. Huang Z, Ruan S T, Sun Y Y, Cheng X Y, Dai J H, Gui P, Yu M J, Zhong Z T, Wu J Y. Bacterial inoculants improved the growth and nitrogen use efficiency of *Pyrus betulifolia* under nitrogen-limited conditions by affecting the native soil bacterial communities. *Applied Soil Ecology*, 2022, **170**(10): 104285
 19. Sindhu S S, Sharma R, Sindhu S, Sehrawat A. Soil fertility improvement by symbiotic rhizobia for sustainable agriculture. In: Panpatte D, Jhala Y, eds. *Soil Fertility Management for Sustainable Development*. Springer, 2019, 101–166
 20. Sun B, Gu L K, Bao L J, Zhang S W, Wei Y X, Bai Z H, Zhuang G Q, Zhuang X L. Application of biofertilizer containing *Bacillus subtilis* reduced the nitrogen loss in agricultural soil. *Soil Biology & Biochemistry*, 2020, **148**: 107911
 21. Sattar A, Naveed M, Ali M, Zahir Z A, Nadeem S M, Yaseen M, Meena V S, Farooq M, Singh R, Rahman M, Meena H N. Perspectives of potassium solubilizing microbes in sustainable food production system: a review. *Applied Soil Ecology*, 2019, **133**(1): 146–159
 22. Cheng Y Y, Narayanan M, Shi X J, Chen X P, Li Z L, Ma Y. Phosphate-solubilizing bacteria: their agroecological function and optimistic application for enhancing agro-productivity. *Science of the Total Environment*, 2023, **901**(1): 166468
 23. Rafique M, Ortas I, Rizwan M, Chaudhary H J, Gurmani A R, Hussain Munis M F. Residual effects of biochar and phosphorus on growth and nutrient accumulation by maize (*Zea mays* L.) amended with microbes in texturally different soils. *Chemosphere*, 2020, **238**: 124710
 24. Talekar O B. Effect of MPKV bacterial consortium on growth and yield of maize. Dissertation for the Doctoral Degree. Rahuri: *Mahatma Phule Krishi Vidyapeeth (MPKV)*, 2024
 25. Sinha D, Tandon P K. An overview of nitrogen, phosphorus and potassium: key players of nutrition process in plants. In: Mishra K, Tandon P K, Srivastava S, eds. *Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants*. Springer Singapore, 2020, 85–117
 26. Wang J J, Li R C, Zhang H, Wei G H, Li Z F. Beneficial bacteria activate nutrients and promote wheat growth under

- conditions of reduced fertilizer application. *BMC Microbiology*, 2020, **20**(1): 38
27. Jin Y Q, Zhu H F, Luo S, Yang W W, Zhang L, Li S S, Jin Q, Cao Q, Sun S R, Xiao M. Role of maize root exudates in promotion of colonization of *Bacillus velezensis* strain S3-1 in rhizosphere soil and root tissue. *Current Microbiology*, 2019, **76**(7): 855–862
 28. Zhang H, Chen F, Zhao H Z, Lu J S, Zhao M J, Hong Q, Huang X. Colonization on cucumber root and enhancement of chlorimuron-ethyl degradation in the rhizosphere by *Hansschlegelia zhihuaiae* S113 and root exudates. *Journal of Agricultural and Food Chemistry*, 2018, **66**(18): 4584–4591
 29. Zhalnina K, Louie K B, Hao Z, Mansoori N, Da Rocha U N, Shi S J, Cho H, Karaoz U, Loqué D, Bowen B P, Firestone M K, Northen T R, Brodie E L. Dynamic root exudate chemistry and microbial substrate preferences drive patterns in rhizosphere microbial community assembly. *Nature Microbiology*, 2018, **3**(4): 470–480
 30. Finkel O M, Castrillo G, Herrera Paredes S, Salas González I, Dangl J L. Understanding and exploiting plant beneficial microbes. *Current Opinion in Plant Biology*, 2017, **38**: 155–163
 31. Correa P A, Nosheen A, Yasmin H, Ali M A. Regulatory role of microbial inoculants to induce salt stress tolerance in horticulture crops. In: Seymen M, Kurtar E S, Erdinc C, Kumar A, eds. Sustainable Horticulture. *Academic Press*, 2022, 125–155
 32. 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. *Frontiers in Plant Science*, 2018, **9**: 1473
 33. Belimov A A, Dodd I C, Hontzas N, Theobald J C, Safronova V I, Davies W J. Rhizosphere bacteria containing 1-aminocyclopropane-1-carboxylate deaminase increase yield of plants grown in drying soil via both local and systemic hormone signalling. *New Phytologist*, 2009, **181**(2): 413–423
 34. Saha I, Datta S, Biswas D. Exploring the role of bacterial extracellular polymeric substances for sustainable development in agriculture. *Current Microbiology*, 2020, **77**(11): 3224–3239
 35. Haque M M, Biswas M S, Mosharaf M K, Haque M A, Islam M S, Nahar K, Islam M M, Shozib H B, Islam M M, Ferdous-E-Elahi. Halotolerant biofilm-producing rhizobacteria mitigate seawater-induced salt stress and promote growth of tomato. *Scientific Reports*, 2022, **12**(1): 5599
 36. Liu C Y, Hao Y, Wu X L, Dai F J, Abd-Allah E F, Wu Q S, Liu S R. Arbuscular mycorrhizal fungi improve drought tolerance of tea plants via modulating root architecture and hormones. *Plant Growth Regulation*, 2024, **102**(1): 13–22
 37. Armada E, Portela G, Roldán A, Azcón R. Combined use of beneficial soil microorganism and agrowaste residue to cope with plant water limitation under semiarid conditions. *Geoderma*, 2014, **232–234**: 640–648
 38. Tiwari S, Lata C, Chauhan P S, Nautiyal C S. *Pseudomonas putida* attunes morphophysiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery. *Plant Physiology and Biochemistry*, 2016, **99**: 108–117
 39. Thomas L, Singh I. Microbial biofertilizers: types and applications. In: Giri B, Prasad R, Wu Q S, Varma A, eds. *Biofertilizers for Sustainable Agriculture and Environment*. Springer, 2019, 1–19
 40. Dinnage R, Simonsen A K, Barrett L G, Cardillo M, Raisbeck-Brown N, Thrall P H, Prober S M. Larger plants promote a greater diversity of symbiotic nitrogen-fixing soil bacteria associated with an Australian endemic legume. *Journal of Ecology*, 2019, **107**(2): 977–991
 41. He Y, Pantigoso H A, Wu Z, Vivanco J M. Co-inoculation of *Bacillus* sp. and *Pseudomonas putida* at different development stages acts as a biostimulant to promote growth, yield and nutrient uptake of tomato. *Journal of Applied Microbiology*, 2019, **127**(1): 196–207
 42. Munir I, Bano A, Faisal M. Impact of phosphate solubilizing bacteria on wheat (*Triticum aestivum*) in the presence of pesticides. *Brazilian Journal of Biology*, 2019, **79**(1): 29–37
 43. Yaghoubi Khanghahi M, Pirdashti H, Rahimian H, Nematzadeh G H, Ghajar Sepanlou M, Salvatori E, Crecchio C. Leaf photosynthetic characteristics and photosystem II photochemistry of rice (*Oryza sativa* L.) under potassium-solubilizing bacteria inoculation. *Photosynthetica*, 2019, **57**(2): 500–511
 44. Ali A M, Awad M Y, Hegab S A, Gawad A M A E, Eissa M A. Effect of potassium solubilizing bacteria (*Bacillus cereus*) on growth and yield of potato. *Journal of Plant Nutrition*, 2021, **44**(3): 411–420
 45. Irshad S, Xie Z M, Wang J, Nawaz A, Luo Y, Wang Y X, Mehmood S, Faheem M. Indigenous strain *Bacillus* XZM assisted phytoremediation and detoxification of arsenic in *Vallisneria denserrulata*. *Journal of Hazardous Materials*, 2020, **381**: 120903
 46. Abou-Aly H E, Youssef A M, Tewfike T A, El-Alkshar E A, El-Meihy R M. Reduction of heavy metals bioaccumulation in sorghum and its rhizosphere by heavy metals-tolerant bacterial consortium. *Biocatalysis and Agricultural Biotechnology*, 2021, **31**(1): 101911
 47. Wang R, Wang C, Feng Q, Liou R M, Lin Y F. Biological inoculant of salt-tolerant bacteria for plant growth stimulation under different saline soil conditions. *Journal of Microbiology and Biotechnology*, 2021, **31**(3): 398–407
 48. Prittesh P, Avnika P, Kinjal P, Jinal H N, Sakthivel K, Amaresan N. Amelioration effect of salt-tolerant plant growth-promoting bacteria on growth and physiological properties of rice (*Oryza sativa*) under salt-stressed conditions. *Archives of Microbiology*, 2020, **202**(9): 2419–2428
 49. Çığ F, Erman M, Ceritoğlu M. Combined application of microbial inoculation and biochar to mitigate drought stress

- in wheat. *Journal of the Institute of Science and Technology*, 2021, **11**: 3528–3538
50. Zhang M, Yang L, Hao R Q, Bai X X, Wang Y, Yu X. Drought-tolerant plant growth-promoting rhizobacteria isolated from jujube (*Ziziphus jujuba*) and their potential to enhance drought tolerance. *Plant and Soil*, 2020, **452**(1–2): 423–440
51. Sharma P, Parakh S K, Singh S P, Parra-Saldívar R, Kim S H, Varjani S, Tong Y W. A critical review on microbes-based treatment strategies for mitigation of toxic pollutants. *Science of the Total Environment*, 2022, **834**: 155444
52. Lebeau T, Braud A, Jézéquel K. Performance of bioaugmentation-assisted phytoextraction applied to metal contaminated soils: a review. *Environmental Pollution*, 2008, **153**(3): 497–522
53. Comte S, Guibaud G, Baudu M. Biosorption properties of extracellular polymeric substances (EPS) towards Cd, Cu and Pb for different pH values. *Journal of Hazardous Materials*, 2008, **151**(1): 185–193
54. Bharagava R N, Mishra S. Hexavalent chromium reduction potential of *Cellulosimicrobium* sp. isolated from common effluent treatment plant of tannery industries. *Ecotoxicology and Environmental Safety*, 2018, **147**: 102–109
55. Maurya A, Kumar P S, Raj A. Characterization of biofilm formation and reduction of hexavalent chromium by bacteria isolated from tannery sludge. *Chemosphere*, 2022, **286**(Pt 2): 131795
56. Tang F H M, Lenzen M, McBratney A, Maggi F. Risk of pesticide pollution at the global scale. *Nature Geoscience*, 2021, **14**(4): 206–210
57. Zhang G C, Wang J, Zhao H, Liu J, Ling W T. PAH degradation and gene abundance in soils and vegetables inoculated with PAH-degrading endophytic bacteria. *Applied Soil Ecology*, 2021, **168**(3): 104193
58. Fu L, Bai Y N, Lu Y Z, Ding J, Zhou D D, Zeng R J. Degradation of organic pollutants by anaerobic methane-oxidizing microorganisms using methyl orange as example. *Journal of Hazardous Materials*, 2019, **364**: 264–271
59. Liu X C, Ge W, Zhang X M, Chai C, Wu J, Xiang D, Chen X Y. Biodegradation of aged polycyclic aromatic hydrocarbons in agricultural soil by *Paracoccus* sp. LXC combined with humic acid and spent mushroom substrate. *Journal of Hazardous Materials*, 2019, **379**: 120820
60. 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. *Environmental Science. Nano*, 2021, **8**(5): 1196–1210
61. Wang L H, Pedersen P B M, Svenning J C. Rewilding abandoned farmland has greater sustainability benefits than afforestation. *npj. Biodiversity*, 2023, **2**(1): 1–4
62. Yan H, Gu S, Li S, Shen W, Zhou X, Yu H, Ma K, Zhao Y, Wang Y, Zheng H, Deng Y, Lu G. Grass-legume mixtures enhance forage production via the bacterial community. *Agriculture, Ecosystems & Environment*, 2022, **338**: 108087
63. Li C, Nie H, Zhang S F, Jia Z H, Ma S L, Li T, Zhai L, Zhang B, Liu X, Zhang J C, Müller C. Mineral-solubilizing microbial inoculant positively affects the multifunctionality of anthropogenic soils in abandoned mining areas. *Journal of Environmental Management*, 2023, **344**: 118553
64. Khan S T, Adil S F, Shaik M R, Alkhatlan H Z, Khan M, Khan M. Engineered nanomaterials in soil: their impact on soil microbiome and plant health. *Plants*, 2022, **11**(1): 109
65. Shukla P, Chaurasia P, Younis K, Qadri O S, Faridi S A, Srivastava G. Nanotechnology in sustainable agriculture: studies from seed priming to post-harvest management. *Nanotechnology for Environmental Engineering*, 2019, **4**(1): 11
66. Usman M, Farooq M, Wakeel A, Nawaz A, Cheema S A, Rehman H, Ashraf I, Sanaullah M. Nanotechnology in agriculture: current status, challenges and future opportunities. *Science of the Total Environment*, 2020, **721**: 137778
67. Madzokere T C, Murombo L T, Chiririwa H. Nano-based slow releasing fertilizers for enhanced agricultural productivity. *Materials Today: Proceedings*, 2021, **45**(6): 3709–3715
68. Jarosz R, Szerement J, Gondek K, Mierzwa-Hersztek M. The use of zeolites as an addition to fertilisers—A review. *Catena*, 2022, **213**(9): 106125
69. Ain ul Q, Hussain HA, Zhang Q, Rasheed A, Imran A, Hussain S, Ahmad N, Bibi H, Ali K S. Use of nano-fertilizers to improve the nutrient use efficiencies in plants. In: Aftab T, Hakeem K R, eds. Sustainable Plant Nutrition. *Elsevier*, 2023, 299–321
70. Chhowalla M. Slow release nanofertilizers for bumper crops. *ACS Central Science*, 2017, **3**(3): 156–157
71. Wahab A, Munir A, Saleem M H, AbdulRaheem M I, Aziz H, Mfarrej M F B, Abdi G. AbdulRaheem M I, Aziz H, Mfarrej M F B, Abdi G. Interactions of metal-based engineered nanoparticles with plants: an overview of the state of current knowledge, research progress, and prospects. *Journal of Plant Growth Regulation*, 2023, **42**(9): 5396–5416
72. De Souza-Torres A, Govea-Alcaide E, Gomez-Padilla E, Masunaga S H, Effenberger F B, Rossi L M, Lopez-Sanchez R, Jardim R F. Fe₃O₄ nanoparticles and *Rhizobium* inoculation enhance nodulation, nitrogen fixation and growth of common bean plants grown in soil. *Rhizosphere*, 2021, **17**: 100275
73. Kumar H, Bhardwaj K, Nepovimova E, Kuča K, Singh Dhanjal D, Bhardwaj S, Bhatia S K, Verma R, Kumar D. Antioxidant functionalized nanoparticles: a combat against oxidative stress. *Nanomaterials*, 2020, **10**(7): 1334
74. Shang Y F, Hasan M K, Ahammed G J, Li M Q, Yin H Q, Zhou J. Applications of nanotechnology in plant growth and crop protection: a review. *Molecules*, 2019, **24**(14): 2558
75. Li M S, Zhang P, Guo Z L, Zhao W C, Li Y B, Yi T J, Cao W D, Gao L, Tian C F, Chen Q, Ren F Z, Rui Y K, White J C, Lynch I. Dynamic transformation of nano-MoS₂ in a soil-plant system empowers its multifunctionality on soybean growth. *Environmental Science & Technology*, 2024, **58**(2):

- 1211–1222
76. Khan M T, Ahmed S, Shah A A, Noor Shah A, Tanveer M, El-Sheikh M A, Siddiqui M H. Influence of zinc oxide nanoparticles to regulate the antioxidants enzymes, some osmolytes and agronomic attributes in *Coriandrum sativum* L. grown under water stress. *Agronomy*, 2021, **11**(10): 2004
 77. Seleiman M F, Almutairi K F, Alotaibi M, Shami A, Alhammad B A, Battaglia M L. Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use. *Plants*, 2021, **10**(1): 2
 78. Salehi H, Chehregani A, Lucini L, Majd A, Gholami M. Morphological, proteomic and metabolomic insight into the effect of cerium dioxide nanoparticles to *Phaseolus vulgaris* L. under soil or foliar application. *Science of the Total Environment*, 2018, **616–617**: 1540–1551
 79. Philippot L, Chenu C, Kappler A, Rillig M C, Fierer N. The interplay between microbial communities and soil properties. *Nature Reviews. Microbiology*, 2024, **22**(4): 226–239
 80. Pérez-Hernández H, Fernández-Luqueño F, Huerta-Lwanga E, Mendoza-Vega J, Álvarez-Solís José D. Effect of engineered nanoparticles on soil biota: do they improve the soil quality and crop production or jeopardize them. *Land Degradation & Development*, 2020, **31**(16): 2213–2230
 81. Singh A, Tiwari S, Pandey J, Lata C, Singh I K. Role of nanoparticles in crop improvement and abiotic stress management. *Journal of Biotechnology*, 2021, **337**: 57–70
 82. Tian H, Kah M, Kariman K. Are nanoparticles a threat to mycorrhizal and rhizobial symbioses? A critical review. *Frontiers in Microbiology*, 2019, **10**: 1660
 83. Sillen W M A, Thijs S, Abbamondi G R, Janssen J, Weyens N, White J C, Vangronsveld J. Effects of silver nanoparticles on soil microorganisms and maize biomass are linked in the rhizosphere. *Soil Biology & Biochemistry*, 2015, **91**: 14–22
 84. Dai Y H, Chen F R, Yue L, Li T, Jiang Z X, Xu Z F, Wang Z Y, Xing B S. Uptake, transport, and transformation of CeO₂ nanoparticles by strawberry and their impact on the rhizosphere bacterial community. *ACS Sustainable Chemistry & Engineering*, 2020, **8**(12): 4792–4800
 85. 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. *Environmental Sciences Europe*, 2019, **31**(1): 15
 86. Li Y, Zhao R Q, Wang L F, Niu L H, Wang C, Hu J X, Wu H N, Zhang W L, Wang P F. Silver nanoparticles and Fe(III) co-regulate microbial community and N₂O emission in river sediments. *Science of the Total Environment*, 2020, **706**: 135712
 87. Lin J J, He F, Su B, Sun M G, Owens G, Chen Z L. The stabilizing mechanism of cadmium in contaminated soil using green synthesized iron oxide nanoparticles under long-term incubation. *Journal of Hazardous Materials*, 2019, **379**: 120832
 88. Rexlin J, Vijayakumar S, Nilavukkarasi M, Vidhya E, Alharthi N S, Sajjad M, Punitha V N, Praseetha P K. Bioengineered ZnO nanoparticles as a nano priming agent in *Cyamopsis tetragonoloba* (L.) Taub. to improve yield and disease resistance. *Applied Nanoscience*, 2023, **13**(9): 5993–6001
 89. Abdelkhalek A, Al-Askar A A. Green synthesized ZnO nanoparticles mediated by mentha spicata extract induce plant systemic resistance against tobacco mosaic virus. *Applied Sciences*, 2020, **10**(15): 5054
 90. Elsherbiny E A, Taher M A. Silicon induces resistance to postharvest rot of carrot caused by *Sclerotinia sclerotiorum* and the possible of defense mechanisms. *Postharvest Biology and Technology*, 2018, **140**: 11–17
 91. Naidu S, Pandey J, Mishra L C, Chakraborty A, Roy A, Singh I K, Singh A. Silicon nanoparticles: synthesis, uptake and their role in mitigation of biotic stress. *Ecotoxicology and Environmental Safety*, 2023, **255**: 114783
 92. El-Shetehy M, Moradi A, Maceroni M, Reinhardt D, Petri-Fink A, Rothen-Rutishauser B, Mauch F, Schwab F. Silica nanoparticles enhance disease resistance in *Arabidopsis* plants. *Nature Nanotechnology*, 2021, **16**(3): 344–353
 93. Lopez-Lima D, Mtz-Enriquez A I, Carrión G, Basurto-Cereceda S, Pariona N. The bifunctional role of copper nanoparticles in tomato: effective treatment for *Fusarium* wilt and plant growth promoter. *Scientia Horticulturae*, 2021, **277**: 109810
 94. Cao X S, Wang C X, Luo X, Yue L, White J C, Elmer W, Dhankher O P, Wang Z Y, Xing B S. Elemental sulfur nanoparticles enhance disease resistance in tomatoes. *ACS Nano*, 2021, **15**(7): 11817–11827
 95. Zhang J, Kothalawala S, Yu C Z. Engineered silica nanomaterials in pesticide delivery: challenges and perspectives. *Environmental Pollution*, 2023, **320**: 121045
 96. El-Saadony M T, Saad A M, Soliman S M, Salem H M, Desoky E S M, Babalghith A O, El-Tahan A M, Ibrahim O M, Ebrahim A A M, Abd El-Mageed T A, Elrys A S, Elbadawi A A, El-Tarabily K A, AbuQamar S F. Role of nanoparticles in enhancing crop tolerance to abiotic stress: a comprehensive review. *Frontiers in Plant Science*, 2022, **13**: 946717
 97. Sheng Y Z, Hu J L, Kukkadapu R, Guo D Y, Zeng Q, Dong H L. Inhibition of extracellular enzyme activity by reactive oxygen species upon oxygenation of reduced iron-bearing minerals. *Environmental Science & Technology*, 2023, **57**(8): 3425–3433
 98. Dilnawaz F, Misra A N, Apostolova E. Involvement of nanoparticles in mitigating plant's abiotic stress. *Plant Stress*, 2023, **10**: 100280
 99. Hayat F, Khanum F, Li J, Iqbal S, Khan U, Javed H U, Razzaq M K, Altaf M A, Peng Y, Ma X Y, Li C Q, Tu P F, Chen J Z. Nanoparticles and their potential role in plant adaptation to abiotic stress in horticultural crops: a review. *Scientia Horticulturae*, 2023, **321**: 112285
 100. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra S M A. Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development*, 2009, **29**(1): 185–212

101. Behboudi F, Tahmasebi Sarvestani Z, Kassae M Z, Modares Sanavi S A M, Sorooshzadeh A. Improving growth and yield of wheat under drought stress via application of SiO₂ nanoparticles. *Journal of Agricultural Science and Technology*, 2018, **20**(7): 1479–1492
102. Semida W M, Abdelkhalik A, Mohamed G F, Abd El-Mageed T A, Abd El-Mageed S A, Rady M M, Ali E F. Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena* L.). *Plants*, 2021, **10**(2): 421
103. Zahedi S M, Moharrami F, Sarikhani S, Padervand M. Selenium, silica nanostructure-based recovery of strawberry plants subjected to drought stress. *Scientific Reports*, 2020, **10**(1): 17672
104. Hellal F, Amer A K, El-Sayed S, El-Azab K. Mitigating the negative effect of water stress on barley by nano silics application. *Plant Archives*, 2020, **20**: 3224–3231
105. Namjoyan S, Sorooshzadeh A, Rajabi A, Aghaalikhani M. Nano-silicon protects sugar beet plants against water deficit stress by improving the antioxidant systems and compatible solutes. *Acta Physiologiae Plantarum*, 2020, **42**(10): 157
106. Ikram M, Raja N I, Javed B, Mashwani Z R, Hussain M, Hussain M, Ehsan M, Rafique N, Malik K, Sultana T, Akram A. Foliar applications of bio-fabricated selenium nanoparticles to improve the growth of wheat plants under drought stress. *Green Processing and Synthesis*, 2020, **9**(1): 706–714
107. Othmani A, Ayed S, Bezzin O, Farooq M, Ayed-Slama O, Slim-Amara H, Ben Younes M. Effect of silicon supply methods on durum wheat (*Triticum durum* Desf.) response to drought stress. *Silicon*, 2021, **13**(9): 3047–3057
108. Behboudi F, Tahmasebi-Sarvestani Z, Kassae M Z, Modarres-Sanavy S A M, Sorooshzadeh A, Mokhtassi-Bidgoli A. Evaluation of chitosan nanoparticles effects with two application methods on wheat under drought stress. *Journal of Plant Nutrition*, 2019, **42**(13): 1439–1451
109. Geange S R, Arnold P A, Catling A A, Coast O, Cook A M, Gowland K M, Leigh A, Notarnicola R F, Posch B C, Venn S E, Zhu L, Nicotra A B. The thermal tolerance of photosynthetic tissues: a global systematic review and agenda for future research. *New Phytologist*, 2021, **229**(5): 2497–2513
110. Mittler R. ROS are good. *Trends in Plant Science*, 2017, **22**(1): 11–19
111. Hassan M U, Chattha M U, Khan I, Chattha M B, Barbanti L, Aamer M, Iqbal M M, Nawaz M, Mahmood A, Ali A. , Aslam M T. Heat stress in cultivated plants: Nature, impact, mechanisms, and mitigation strategies—A review. *Plant Biosystems*, 2021, **155**(2): 211–234
112. Aslam M, Fakher B, Ashraf M A, Cheng Y, Wang B R, Qin Y. Plant low-temperature stress: signaling and response. *Agronomy*, 2022, **12**(3): 702
113. Adhikari L, Baral R, Paudel D, Min D, Makaju S O, Poudel H P, Acharya J P, Missaoui A M. Cold stress in plants: strategies to improve cold tolerance in forage species. *Plant Stress*, 2022, **4**(3): 100081
114. Kardavan Ghabel V, Karamian R. Effects of TiO₂ nanoparticles and spermine on antioxidant responses of *Glycyrrhiza glabra* L. to cold stress. *Acta Botanica Croatica*, 2020, **79**(2): 137–147
115. Wang A B, Li J Y, AL-Huqail A A, AL-Harbi M S, Ali E F, Wang J, Ding Z, Rekaby S A, Ghoneim A M, Eissa M A. Mechanisms of chitosan nanoparticles in the regulation of cold stress resistance in banana plants. *Nanomaterials*, 2021, **11**(10): 2670
116. Elsheery N I, Sunoj V S J, Wen Y, Zhu J J, Muralidharan G, Cao K F. Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. *Plant Physiology and Biochemistry*, 2020, **149**: 50–60
117. Manzoor N, Ahmed T, Noman M, Shahid M, Nazir M M, Ali L, Alnusaire T S, Li B, Schulin R, Wang G. Iron oxide nanoparticles ameliorated the cadmium and salinity stresses in wheat plants, facilitating photosynthetic pigments and restricting cadmium uptake. *Science of the Total Environment*, 2021, **769**: 145221
118. Rakgotho T, Ndou N, Mulaudzi T, Iwuoha E, Mayedwa N, Ajayi R F. Green-synthesized zinc oxide nanoparticles mitigate salt stress in sorghum bicolor. *Agriculture*, 2022, **12**(5): 597
119. Sarkar R D, Kalita M C. Green synthesized Se nanoparticle-mediated alleviation of salt stress in field mustard, TS-36 variety. *Journal of Biotechnology*, 2022, **359**: 95–107
120. Jiang W J, Meng L S, Liu F T, Sheng Y Z, Chen S M, Yang J L, Mao H R, Zhang J, Zhang Z, Ning H. Distribution, source investigation, and risk assessment of topsoil heavy metals in areas with intensive anthropogenic activities using the positive matrix factorization (PMF) model coupled with self-organizing map (SOM). *Environmental Geochemistry and Health*, 2023, **45**(8): 6353–6370
121. Rai P K, Lee S S, Zhang M, Tsang Y F, Kim K H. Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, 2019, **125**: 365–385
122. Kah M, Tufenkji N, White J C. Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*, 2019, **14**(6): 532–540
123. Qian Y T, Qin C D, Chen M M, Lin S J. Nanotechnology in soil remediation—Applications vs. implications. *Ecotoxicology and Environmental Safety*, 2020, **201**: 110815
124. Wang Z Y, Yue L, Dhankher O P, Xing B S. Nano-enabled improvements of growth and nutritional quality in food plants driven by rhizosphere processes. *Environment International*, 2020, **142**: 105831
125. Rico C M, Morales M I, McCreary R, Castillo-Michel H, Barrios A C, Hong J, Tafoya A, Lee W Y, Varela-Ramirez A, Peralta-Videa J R, Gardea-Torresdey J L. Cerium oxide nanoparticles modify the antioxidative stress enzyme activities and macromolecule composition in rice seedlings. *Environmental Science & Technology*, 2013, **47**(24):

- 14110–14118
126. Manzoor N, Ali L, Ahmed T, Rizwan M, Ali S, Shahid M S, Schulin R, Liu Y, Wang G. Silicon oxide nanoparticles alleviate chromium toxicity in wheat (*Triticum aestivum* L.). *Environmental Pollution*, 2022, **315**: 120391
127. Manzoor N, Ali L, AL-Huqail A A, Alghanem S M S, Al-Haithloul H A S, Abbas T, Chen G, Huan L, Liu Y, Wang G. Comparative efficacy of silicon and iron oxide nanoparticles towards improving the plant growth and mitigating arsenic toxicity in wheat (*Triticum aestivum* L.). *Ecotoxicology and Environmental Safety*, 2023, **264**: 115382
128. Montanha G S, Rodrigues E S, Marques J P R, de Almeida E, Colzato M, Pereira de Carvalho H W. Zinc nanocoated seeds: an alternative to boost soybean seed germination and seedling development. *SN Applied Sciences*, 2020, **2**(5): 857
129. He Y J, Hu R R, Zhong Y J, Zhao X L, Chen Q, Zhu H W. Graphene oxide as a water transporter promoting germination of plants in soil. *Nano Research*, 2018, **11**(4): 1928–1937
130. Nguyen D T C, Le H T N, Nguyen T T, Nguyen T T T, Bach L G, Nguyen T D, Tran T V. Multifunctional ZnO nanoparticles bio-fabricated from *Canna indica* L. flowers for seed germination, adsorption, and photocatalytic degradation of organic dyes. *Journal of Hazardous Materials*, 2021, **420**: 126586
131. García-López J I, Zavala-García F, Olivares-Sáenz E, Lira-Saldívar R H, Díaz Barriga-Castro E, Ruiz-Torres N A, Ramos-Cortez E, Vázquez-Alvarado R, Niño-Medina G. Zinc oxide nanoparticles boosts phenolic compounds and antioxidant activity of *Capsicum annuum* L. during germination. *Agronomy*, 2018, **8**(10): 215
132. Estrada-Urbina J, Cruz-Alonso A, Santander-González M, Méndez-Albores A, Vázquez-Durán A. Nanoscale zinc oxide particles for improving the physiological and sanitary quality of a Mexican landrace of red maize. *Nanomaterials*, 2018, **8**(4): 247
133. Rai-Kalal P, Jajoo A. Priming with zinc oxide nanoparticles improve germination and photosynthetic performance in wheat. *Plant Physiology and Biochemistry*, 2021, **160**: 341–351
134. Gomaa M A, Kandil E E, El-Dein A A M Z, Abou-Donia M E M, Ali H M, Abdelsalam N R. Increase maize productivity and water use efficiency through application of potassium silicate under water stress. *Scientific Reports*, 2021, **11**(1): 224
135. Oliva K M E, da Silva F B V, Araújo P R M, de Oliveira E C A, do Nascimento C W A. Amorphous silica-based fertilizer increases stalks and sugar yield and resistance to stalk borer in sugarcane grown under field conditions. *Journal of Soil Science and Plant Nutrition*, 2021, **21**(3): 2518–2529
136. Ahmed T, Noman M, Manzoor N, Shahid M, Abdullah M, Ali L, Wang G, Hashem A, Al-Arjani A B F, Alqarawi A A, Abd_Allah E F, Li B. Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice via triggering the stress responsive genetic mechanisms and nutrient acquisition. *Ecotoxicology and Environmental Safety*, 2021, **209**: 111829
137. Ahmed T, Masood H A, Noman M, AL-Huqail A A, Alghanem S M S, Khan M M, Muhammad S, Manzoor N, Rizwan M, Qi X J, Abeer A H A, Li B. Biogenic silicon nanoparticles mitigate cadmium (Cd) toxicity in rapeseed (*Brassica napus* L.) by modulating the cellular oxidative stress metabolism and reducing Cd translocation. *Journal of Hazardous Materials*, 2023, **459**: 132070
138. Ahmed T, Shahid M, Noman M, Niazi M B K, Mahmood F, Manzoor I, Zhang Y, Li B, Yang Y, Yan C Q, Chen J P. Silver nanoparticles synthesized by using *Bacillus cereus* SZT1 ameliorated the damage of bacterial leaf blight pathogen in rice. *Pathogens*, 2020, **9**(3): 160
139. Ahmed T, Noman M, Jiang H B, Shahid M, Ma C X, Wu Z F, Nazir M M, Ali M A, White J C, Chen J P, Li B. Bioengineered chitosan-iron nanocomposite controls bacterial leaf blight disease by modulating plant defense response and nutritional status of rice (*Oryza sativa* L.). *Nano Today*, 2022, **45**: 101547
140. Iqbal M, Raja N I, Mashwani Z U R, Wattoo F H, Hussain M, Ejaz M, Saira H. Assessment of AgNPs exposure on physiological and biochemical changes and antioxidative defence system in wheat (*Triticum aestivum* L) under heat stress. *IET Nanobiotechnology/IET*, 2019, **13**(2): 230–236
141. Hassan N S, Salah El Din T A, Hendawey M H, Borai I H, Mahdi A A. Magnetite and zinc oxide nanoparticles alleviated heat stress in wheat plants. *Current Nanomaterials*, 2018, **3**(1): 32–43
142. Ikhajiagbe B, Igiebor F A, Ogwu M C. Growth and yield performances of rice (*Oryza sativa* var. *nerica*) after exposure to biosynthesized nanoparticles. *Bulletin of the National Research Center*, 2021, **45**(1): 62
143. Shakoore N, Adeel M, Zain M, Zhang P, Ahmad M A, Farooq T, Zhou P F, Azeem I, Rizwan M, Guo K R, Jilani G, Ahmar S, Maqbool S, Ming X, Rui Y K. Exposure of cherry radish (*Raphanus sativus* L. var. *Radculus Pers*) to iron-based nanoparticles enhances its nutritional quality by triggering the essential elements. *NanoImpact*, 2022, **25**: 100388
144. Lou L P, Huang Q, Lou Y L, Lu J R, Hu B L, Lin Q. Adsorption and degradation in the removal of nonylphenol from water by cells immobilized on biochar. *Chemosphere*, 2019, **228**: 676–684
145. Zhang Y, Liu S, Niu L L, Su A X, Li M Y, Wang Y Q, Xu Y. Sustained and efficient remediation of biochar immobilized with *Sphingobium abikonense* on phenanthrene-copper co-contaminated soil and microbial preferences of the bacteria colonized in biochar. *Biochar*, 2023, **5**(1): 43
146. Liu M B, Wang S L, Yang M, Wu Y N, Nan Z R. Combined treatment of heavy metals in water and soil by biochar and manganese-oxidizing bacteria. *Journal of Soils and Sediments*, 2023, **23**(1): 145–155
147. Thies J E, Rillig M C. Characteristics of biochar: Biological properties. In: Lehmann J, Joseph S, eds. *Biochar for Environmental Management*. Taylor & Francis, 2009, 85–105
148. Husna N, Budianta D, Munandar M, Napoleon A. Evaluation

- of several biochar types as inoculant carrier for indigenous phosphate solubilizing microorganism from acid sulphate soil. *Journal of Ecological Engineering*, 2019, **20**(6): 1–8
149. Xiang L, Harindintwali J D, Wang F, Redmile-Gordon M, Chang S X, Fu Y H, He C, Muhoza B, Brahushi F, Bolan N, Jiang X, Ok Y S, Rinklebe J, Schaeffer A, Zhu Y, Tiedje J M, Xing B. Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology*, 2022, **56**(23): 16546–16566
 150. Pokharel P, Ma Z L, Chang S X. Biochar increases soil microbial biomass with changes in extra-and intracellular enzyme activities: a global meta-analysis. *Biochar*, 2020, **2**(1): 65–79
 151. Yan T T, Xue J H, Zhou Z D, Wu Y B. Biochar-based fertilizer amendments improve the soil microbial community structure in a karst mountainous area. *Science of the Total Environment*, 2021, **794**: 148757
 152. Sun D, Hale L, Crowley D. Nutrient supplementation of pinewood biochar for use as a bacterial inoculum carrier. *Biology and Fertility of Soils*, 2016, **52**(4): 515–522
 153. Yan W K, Liu Y T, Malacrinò A, Zhang J Y, Cheng X L, Rensing C, Zhang Z Y, Lin W X, Zhang Z, Wu H M. Combination of biochar and PGPBs amendment suppresses soil-borne pathogens by modifying plant-associated microbiome. *Applied Soil Ecology*, 2024, **193**: 105162
 154. Bai X X, Huang Y W, Ren W, Coyne M, Jacinthe P A, Tao B, Hui D F, Yang J, Matocha C. Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis. *Global Change Biology*, 2019, **25**(8): 2591–2606
 155. Ali L, Manzoor N, Li X, Naveed M, Nadeem S M, Waqas M R, Khalid M, Abbas A, Ahmed T, Li B, Yan J. Impact of corn cob-derived biochar in altering soil quality, biochemical status and improving maize growth under drought stress. *Agronomy*, 2021, **11**(11): 2300
 156. Liu Z W, Zhang W, Ma R L, Li S X, Song K Y, Zheng J F, Wang Y, Bian R J, Zhang X H, Pan G X. Biochar-plant interactions enhance nonbiochar carbon sequestration in a rice paddy soil. *Communications Earth & Environment*, 2023, **4**(1): 494
 157. Liu Q, Zhang Y H, Liu B J, Amonette J E, Lin Z B, Liu G, Ambus P, Xie Z B. How does biochar influence soil N cycle? A meta-analysis. *Plant and Soil*, 2018, **426**(1–2): 211–225
 158. Zhang L Y, Jing Y M, Chen C R, Xiang Y Z, Rezaei Rashti M, Li Y T, Deng Q, Zhang R D. Effects of biochar application on soil nitrogen transformation, microbial functional genes, enzyme activity, and plant nitrogen uptake: a meta-analysis of field studies. *Global Change Biology. Bioenergy*, 2021, **13**(12): 1859–1873
 159. Yan S H, Zhang S L, Yan P K, Aurangzeib M. Effect of biochar application method and amount on the soil quality and maize yield in Mollisols of Northeast China. *Biochar*, 2022, **4**(1): 56
 160. Mahmoud E, El-Beshbeshy T, El-Kader N A, El Shal R, Khalafallah N. Impacts of biochar application on soil fertility, plant nutrients uptake and maize (*Zea mays* L.) yield in saline sodic soil. *Arabian Journal of Geosciences*, 2019, **12**(23): 719
 161. Choudhary T K, Khan K S, Hussain Q, Ashfaq M. Nutrient availability to maize crop (*Zea mays* L.) in biochar amended alkaline subtropical soil. *Journal of Soil Science and Plant Nutrition*, 2021, **21**(2): 1293–1306
 162. Luo S S, Wang S J, Tian L, Li S Q, Li X J, Shen Y F, Tian C J. Long-term biochar application influences soil microbial community and its potential roles in semiarid farmland. *Applied Soil Ecology*, 2017, **117–118**: 10–15
 163. Singh H, Northup B K, Rice C W, Prasad P V. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*, 2022, **4**(1): 8
 164. Zulfiqar B, Raza M A S, Saleem M F, Aslam M U, Iqbal R, Muhammad F, Amin J, Ibrahim M A, Khan I H. Biochar enhances wheat crop productivity by mitigating the effects of drought: insights into physiological and antioxidant defense mechanisms. *PLoS One*, 2022, **17**(4): e0267819
 165. Chen X, Liu L, Yang Q Y, Xu H N, Shen G Q, Chen Q C. Optimizing biochar application rates to improve soil properties and crop growth in saline-alkali soil. *Sustainability*, 2024, **16**(6): 2523
 166. Taheri M A R, Astaraei A R, Lakzian A, Emami H. The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil. *Plant and Soil*, 2024, **499**(1–2): 221–236
 167. Aydin E, Šimanský V, Horák J, Igaz D. Potential of biochar to alternate soil properties and crop yields 3 and 4 years after the application. *Agronomy*, 2020, **10**(6): 889
 168. Ali I, He L, Ullah S, Quan Z, Wei S Q, Iqbal A, Munsif F, Shah T, Xuan Y, Luo Y Q, Li T Y, Jiang L G. Biochar addition coupled with nitrogen fertilization impacts on soil quality, crop productivity, and nitrogen uptake under double-cropping system. *Food and Energy Security*, 2020, **9**(3): e208
 169. Zhao W, Zhou Q, Tian Z Z, Cui Y T, Liang Y, Wang H Y. Apply biochar to ameliorate soda saline-alkali land, improve soil function and increase corn nutrient availability in the Songnen Plain. *Science of the Total Environment*, 2020, **722**: 137428
 170. Dong H L, Zeng Q, Sheng Y Z, Chen C M, Yu G, Kappler A. Coupled iron cycling and organic matter transformation across redox interfaces. *Nature Reviews. Earth & Environment*, 2023, **4**(9): 659–673
 171. Yuan H J, Zhang Z J, Li M Y, Clough T, Wrage-Monning N, Qin S P, Ge T D, Liao H P, Zhou S G. Biochar's role as an electron shuttle for mediating soil N₂O emissions. *Soil Biology & Biochemistry*, 2019, **133**: 94–96
 172. Yuan D, Wang G Q, Hu C G, Zhou S, Clough T J, Wrage-Mönning N, Luo J F, Qin S P. Electron shuttle potential of biochar promotes dissimilatory nitrate reduction to ammonium in paddy soil. *Soil Biology & Biochemistry*, 2022, **172**: 108760
 173. Zhou G W, Yang X R, Li H, Marshall C W, Zheng B X, Yan Y,

- Su J Q, Zhu Y G. Electron shuttles enhance anaerobic ammonium oxidation coupled to iron(III) reduction. *Environmental Science & Technology*, 2016, **50**(17): 9298–9307
174. Dong H L, Coffin E S, Sheng Y Z, Duley M L, Khalifa Y M. Microbial reduction of Fe(III) in nontronite: role of biochar as a redox mediator. *Geochimica et Cosmochimica Acta*, 2023, **345**(1–2): 102–116
175. Villada E, Velasquez M, Gómez A M, Correa J D, Saldarriaga J F, López J E, Tamayo A. Combining anaerobic digestion slurry and different biochars to develop a biochar-based slow-release NPK fertilizer. *Science of the Total Environment*, 2024, **927**: 171982
176. Glaser B, Lehr V I. Biochar effects on phosphorus availability in agricultural soils: a meta-analysis. *Scientific Reports*, 2019, **9**(1): 9338
177. Ye Z X, Zhang L M, Huang Q Y, Tan Z X. Development of a carbon-based slow release fertilizer treated by bio-oil coating and study on its feedback effect on farmland application. *Journal of Cleaner Production*, 2019, **239**(8): 118085
178. Yasmeen T, Arif M S, Shahzad S M, Riaz M, Tufail M A, Mubarik M S, Ahmad A, Ali S, Albasher G, Shakoor A. Abandoned agriculture soil can be recultivated by promoting biological phosphorus fertility when amended with nano-rock phosphate and suitable bacterial inoculant. *Ecotoxicology and Environmental Safety*, 2022, **234**: 113385
179. Rubel R I, Wei L. Biochar-based controlled release nitrogen fertilizer coated with polylactic acid. *Journal of Polymers and the Environment*, 2022, **30**(10): 4406–4417
180. Ghorbanpour M, Mohammadi H, Kariman K. Nanosilicon-based recovery of barley (*Hordeum vulgare*) plants subjected to drought stress. *Environmental Science: Nano*, 2020, **7**(2): 443–461
181. Manzoor N, Ali L, Ahmed T, Noman M, Adrees M, Shahid M S, Ogunyemi S O, Radwan K S, Wang G, Zaki H E. Recent advancements and development in nano-enabled agriculture for improving abiotic stress tolerance in plants. *Frontiers in Plant Science*, 2022, **13**: 951752