



REVIEW ARTICLE

Mitigating drought stress in agriculture: Biogenic nanoparticles and their synergistic interaction with environmental components

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Abstract

Abiotic stresses like extreme temperatures, drought, salinity, flood and heavy metals pose serious challenges to global agriculture, resulting in decreased productivity, food insecurity and economic losses. Nanotechnology is now recognised as a radical approach in agricultural science, providing promising solutions to mitigate the adverse impacts of abiotic stressors on plant growth and development. Nanoparticles (NPs) have drawn attention for their potential to address these challenges by improving resource use efficiency, reducing pollution, preventing diseases and promoting sustainability, number of tactics meant to improve crop productivity and quality, reduce nutritional deficiencies and increase stress tolerance. Because of their special characteristics, NPs can act as potent sensors and alter vital physiological and biochemical functions in plants. They also provide novel ways for plants to adjust to shifting environmental circumstances, increasing resilience. Since drought stress impairs nutrient transport and growth and impacts all phases of plant development, it stands out as a serious danger to global food security. The increased activity of antioxidant enzymes, which are essential for preserving cellular integrity and redox equilibrium, is frequently linked to this mitigation. Nano-biotechnology is a viable way to address a number of biotic and abiotic variables limiting output in areas like India, where raising agricultural productivity is essential to supporting a sizable population. Nano-biotechnology has the ability to transform plant growth regulation and stress reduction in agriculture by effectively regulating drought stress by the application of appropriate NP concentrations. This would ensure increased output across a variety of crops.

Keywords: biogenic; microbial; nano-particles; nanotechnology; plant growth

Introduction

By 2050, the world's population is expected to be more than 9.7 billion people. This will place unprecedented demand on agricultural infrastructure to make sure there is enough food for

everyone (1). Agriculture will continue to be very important for economic development and food security, especially in emerging countries where most people work in farming. But traditional farming methods have more than one problem. These include small land holdings, bad irrigation systems, limited access to high-

quality crops, too much usage of pesticides and chemical fertilisers and bad automation. These problems lead to soil deterioration, erosion and lower production (2, 3). Plants are also hurt by biotic stressors (such infections, insects and parasites) and abiotic stresses (including drought, salt and severe temperatures). Drought pressure is one of the most significant abiotic factors that limits agricultural productivity across the world. Drought strain is the physiological and biochemical damage that flowers suffer from when they don't get enough water for a long time (4). This is usually due to less rain, lower groundwater levels and more evaporation. It slows down photosynthesis, nutrient absorption and cellular metabolism, which in turn slows down plant growth and production. The United Nations World Water Development Report (2018) says that drought affects over fifty-five million people per year and might force up to seven hundred million people to move by 2030. Nanotechnology has made new progress and nanoparticles (NPs) may be able to help plants deal with drought stress. Nanoparticles are materials that are between 1 and 100 nanometers in size. They have special physical and chemical properties, including a huge surface area, high reactivity and the ability to release substances in a controlled fashion (5).

- a. Their use in farming has shown to be helpful, such as keeping soil moisture and making it easier for plants to hold onto water.
- b. Their use also makes nutrients more available and increases how well plants take them up.
- c. It also helps protect plant cells from oxidative and osmotic stress, which may cause damage.
- d. The process includes activating pathways that respond to stress to make plants more resistant to drought.

There are two main types of nanoparticles: biogenic and non-biogenic. Biogenic nanoparticles are made by using biological systems like plants, bacteria, fungus or algae. They are thought to be better for the environment since they are less harmful and break down naturally. For example, silver nanoparticles may be generated from plant extracts, zinc oxide nanoparticles can be crafted from microorganisms and silica nanoparticles may be crafted from residual crops (6, 7). People say that those biogenic NPs could assist seeds sprout, roots develop and flowers stay at some point of dry spells. But there are still demanding situations, along with discrepancies in how they're made, concerns about their stability and probably threats to the surroundings.

On the other hand, non-biogenic nanoparticles are made in a lab or in the body using methods including sol-gel, hydrothermal, or vapor deposition. They provide you some control over length and shape, but if you don't keep an eye on them, they might be more dangerous to the environment and more poisonous.

So, adding biogenic nanoparticles to farming is a long-term way to make crops more resistant to drought stress (8). Nanoparticle software may help make agricultural systems more robust by improving water-use efficiency and lowering harm from things that aren't living. This is important since the world needs more food, but there isn't enough water to grow it (9).

Biogenic nanoparticles: definition, synthesis and characterisation

Biogenic nanoparticles are nanomaterials made from living things like vegetation, microorganisms, fungi, algae or enzymes. These

organisms are characterised as natural reducing and stabilising agents throughout the method of making nanoparticles. This biological method produces biogenic nanoparticles that are better for the surroundings than chemically made nanoparticles since it does not use hazardous chemical substances and creates fewer troubles for the ecosystem (10). In agriculture, several biogenic nanoparticles have been studied, seeing that they have many uses. These consist of silver (Ag-NPs), zinc oxide (ZnO-NPs), iron oxide (Fe_3O_4 -NPs), titanium dioxide (TiO_2 -NPs), copper oxide (CuO-NPs) and silicon nanoparticles (Si-NPs). These nanoparticles are very crucial for making plants grow higher and produce more by assisting seeds to germinate, roots to grow, chlorophyll to shape, nutrients to get absorbed and the general metabolism of plants (11). They additionally assist plants in dealing with abiotic challenges like drought by means of making it easier for them to take in water, converting the interest of antioxidant enzymes, keeping osmotic equilibrium and shielding cell structures from oxidative damage (12). Also, many biogenic nanoparticles have antimicrobial and pesticidal abilities, which means that they may be used as nano fungicides, nano bactericides and nano pesticides to govern pests and sicknesses better than everyday agrochemicals. Biogenic nanoparticles have numerous correct matters about them, but additionally they have a few bad matters. Biological synthesis may additionally cause particles to have exclusive sizes, shapes and surface features that may change how nicely they work within the field (13). Producing biogenic nanoparticles on a big scale continues to be hard because it needs a whole lot of biomass, takes a long time to make and may turn out to be infected, specifically in microbial structures (14). Biogenic nanoparticles are thought to be better for the environment; however, the usage of too much of them may additionally still be dangerous to vegetation, forestall their development, change the way vitamins cycle, or harm soil microbial populations (15). We do not yet completely recognise what is going to happen to them in the end, along with whether they'll live inside the ecosystem, alternate in soil, or leak into water bodies (16). So, despite the fact that biogenic nanoparticles have plenty of ability for sustainable agriculture, they want to be carefully adjusted, watched and backed by using, in addition, a look to make sure they're secure and top for the surroundings.

The advent of nanotechnology in the 1960s marked the beginning of a new era in materials research. In order to develop materials at the nanoscale, the subject has brought together a number of academic disciplines, including science, materials design, medicine and physical science. According to nano-particles are made up of a variety of materials with dimensions less than 100 nm. They are categorised as 0-layered (0D), 1-layered (1D) and so forth based on the number of aspects to which an electron can be attached. Circles (0D), wires and poles (1D) and delicate films (2D) are all included in some of the standard computations. Because of their remarkable electrical, appealing and physiochemical characteristics-such as size control, an expanded surface area to volume proportion and functionalities-nano-particle amalgamation is essential. The main causes of these new characteristics of nano-particles are (i) electron repression in these particles, (ii) alterations in molecule size to modify bandgap energies and (iii) a large surface to volume ratio (16). In terms of their mass structure, these new nano-particle characteristics-such as their organic, chemical, electrical, optical and appealing qualities-differ greatly from those of comparable materials. According to nanomaterials provide enhanced Raman and Rayleigh dispersing

properties in metal nanoparticles (NPs), super magnetic properties in materials that are appealing and a quantum impact in semiconductors (17). According to these nanoparticles from the advanced building blocks for applications in biomedicine, chemistry, electronics and optics (18). Recently, nanoparticles have also found use in the food, material, petroleum and natural industries (19). In the recent decade, there has been an increase in the investigation of other metal nanoparticles, such as copper, palladium, platinum and various metal oxides, whereas before, metal nanoparticles, like gold and silver, were the focus of intense attention (20).

Biogenic synthesis of nano-particles

Numerous unique nanostructures can be delivered by microorganisms. Because of this, scientists are becoming more interested in employing these microbes to add nanostructures for various uses (21). The combination of organically interfered and stimulated microorganisms and growths can form inorganic particles. Nanostructures of desired calculations and organization may be formed by managing the organic amalgamation (22). The organic mix of nano-particles is nevertheless limited in terms of molecular math controllability and interaction adaptability, regardless matter how precise the nano-particle physicochemical union. Regardless, naturally occurring union has allowed scientists to design inorganic nanoparticles using common metal precursors and also provides a wide range of organization (23). Green growth, parasites and bacteria are examples of microorganisms that are increasingly being used to create nanoparticles. There are many different types of organisms that generally react differently to metal precursors to form nano-particles (24). Microorganisms and parasites, for example, are capable of both intracellular and extracellular production and the two cycles have different paths in different organisms. Metal particles are moved via intracellular union through the cell wall, where the positively charged particles attach to the negatively charged wall. These particles are reduced to metal nano-particles by the cells' catalysts (25). Gold nano-particle mix using *Lactobacillus kimchicus* microorganisms is demonstrated. The formation of nanoclusters through an electrostatic connection point is triggered by the nucleation of HAuCl₄ particles at the beginning of the contact (26). Nanoclusters are gradually transferred throughout the organism's cell wall a short while later.

The extracellular mix of nano-particles' mechanism keeps track of the overall number of metal particles on the cell surface and incorporates decreasing particles via compounds (27). Used *Cupriavidas* sp. for silver nano-particle extracellular union. According to the review, silver particles are captured on the cell surface and reduced to nuclear silver nano-particles by the catalyst nitrate reductase. Massive research efforts were made to plan such ways for creating a large number of NPs (including titanium oxide, palladium, silver, gold and so on) (28). Fig. 1 illustrates the intracellular and cell-bound synthesis of gold nanoparticles (AuNPs) using *Lactobacillus kimchicus* DCY51^T. In this biological process, gold ions (Au³⁺) either attach to the bacterial cell surface or enter the cell interior. Microbial enzymes and reducing biomolecules convert these ions into elemental gold (Au⁰), initiating nanoparticle formation. Stabilising proteins and metabolites then cap and protect the nanoparticles, ensuring controlled size and preventing aggregation. Overall, the figure highlights eco-friendly, biologically regulated nanoparticle synthesis as a sustainable alternative to conventional chemical methods (29). Table 1 provides an overview of the major nanoparticles currently used in agriculture, highlighting their diverse functions and benefits (30). It summarises key nanoparticles-such as silver, zinc oxide, titanium dioxide, silica, iron oxide and biogenic nanoparticles-along with their roles in nutrient delivery, stress tolerance, disease suppression and soil health improvement. The Table also reflects how nano-enabled formulations enhance nutrient-use efficiency, support drought resilience and enable controlled release mechanisms compared to traditional inputs. Overall, Table 1 demonstrates the expanding role of nanotechnology in developing sustainable, efficient and climate-resilient agricultural practices.

Characterisation of nano-particles

Nano-particles are useful for a variety of applications because of their unique characteristics and features. In order to ensure that they are fit for purpose, it is imperative that they be evaluated through extensive characterisation, particularly for biomedical applications (31). Various techniques and hardware that can provide the required data are used to achieve this. The most often used techniques include Raman spectroscopy (RS), energy-dispersive X-beam spectroscopy (EDS), nuclear power microscopy (NPM), Fourier change infrared (FT-IR) spectroscopy, filtering and

Table 1. Nanoparticles used in agriculture and their applications (63)

Nanoparticle	Mode of synthesis	Agricultural application	Benefits	Limitations / Concerns
Silver (Ag-NPs)	Plant extract, microbial, chemical	Nano pesticide, antimicrobial agent	Controls bacterial and fungal pathogens, enhances seed germination, stress tolerance	Phytotoxicity at high doses, soil microbial disruption
Zinc Oxide (ZnO-NPs)	Plant extract, microbial, chemical	Nanofertilizer, growth enhancer	Improves photosynthesis, drought and salinity tolerance, nutrient uptake	Over-application may cause oxidative stress
Iron Oxide (Fe ₃ O ₄ -NPs)	Microbial, chemical	Nanofertilizer, stress alleviation	Enhances chlorophyll synthesis, improves drought tolerance, micronutrient supply	Limited data on long-term soil accumulation
Titanium Dioxide (TiO ₂ -NPs)	Plant extract, chemical	Growth promoter, stress alleviation	Improves photosynthesis, enhances ROS scavenging, increases yield	Environmental persistence, potential phytotoxicity
Silicon (Si-NPs)	Plant extract, chemical	Stress tolerance, nanofertilizer	Strengthens cell walls, improves drought and salinity tolerance, enhances nutrient uptake	Cost of large-scale production
Copper Oxide (CuO-NPs)	Microbial, chemical	Nano pesticide, micronutrient source	Controls pathogens, improves enzymatic activities	High doses may inhibit plant growth, toxic to beneficial microbes
Selenium (Se-NPs)	Microbial, chemical	Nutrient supplement, stress alleviation	Enhances antioxidant activity, improves drought tolerance	Narrow concentration range; toxicity at high levels
Gold (Au-NPs)	Microbial, plant extract, chemical	Growth promoter, nano sensor	Stimulates seed germination, enhances enzymatic activity	High cost, limited field-scale studies
Carbon-based NPs (CNTs, graphene)	Chemical / physical	Growth promoter, nutrient delivery	Enhances water and nutrient uptake, stress resistance	Potential soil contamination, uncertain biodegradability

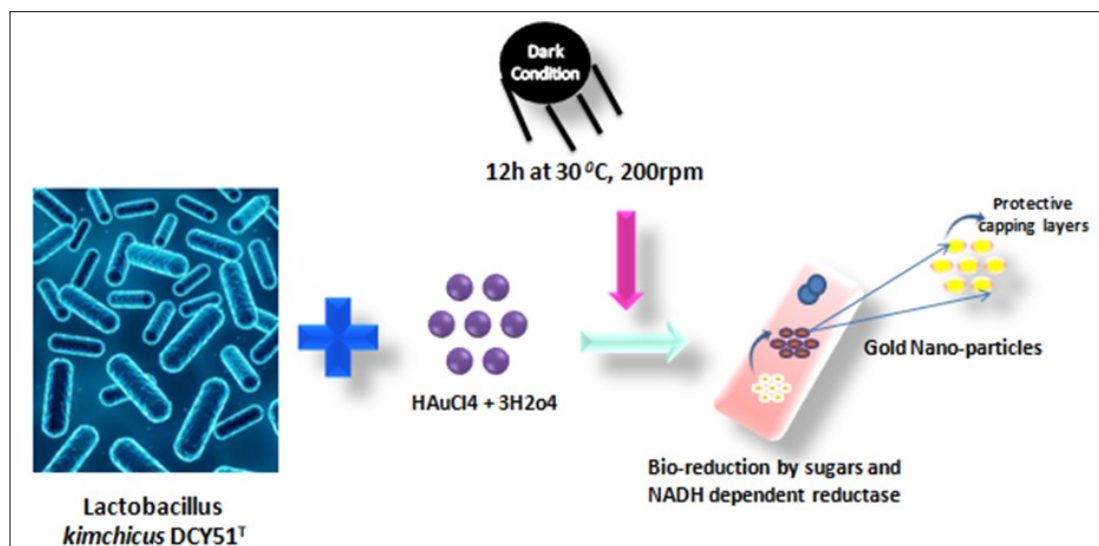


Fig. 1. Mechanism of the intracellular-cell bound synthesis of gold nanoparticles (AuNPs) using *Lactobacillus kimchicus* DCY51^T (29).

transmission electron microscopy (SEM/TEM), unique light dissipating (DLS) and nuclear power microscopy (AFM) (32, 33). Nano-particle size, shape, structure, surface characteristics and interactions with materials such as human tissues are all considered using these techniques (34). The following Table 1 provides a summary of some of the methods used to characterise the physicochemical characteristics of nanoparticles. The companion audit report "characterisation procedures for nanoparticles: correlation and complementarity after examining nano-particle properties" (35), is advised for a thorough overview of nanoparticle characterisation techniques. In Table 2, techniques for characterisation of nanoparticles are shown (29).

Geometry

The unique characteristics of nano-particles that determine their performance in specific applications are determined by their size and shape. High-level hardware with amazing amplification and aim is used to examine the size and condition of nanostructures at sizes less than 100 nm. High-goal transmission electron microscopy (HRTEM) and field-outflow examining electron microscopy (FeSEM), which can image and differentiate nano-particle nuclear architecture, are two of the most widely used nanoscale imaging techniques. TEM can provide details about the nanoparticles' size, shape, aggregation state and morphology by using light emission to illuminate them. According to a study, a model transmission electron microscopy (TEM) image displays gold nanoparticles with a typical size of 20.93 nm (36).

Surface morphology

Surface morphology is often shown using AFM, SEM and TEM. The TEM is more capable of providing creation and morphology, enabling the nuclear scale aim. Since SEM uses light emission to visualize the sample's outer layer, the example must be conductive

before further research can be done. Despite having a less favorable objective, SEM is used more frequently than TEM and may examine the collection and morphology. Another important technique that can analyse the location, size of molecules and movement of nanoparticles is AFM, which can be used in a variety of environments, including fluid, air and vacuum (37).

Attractive properties

Since iron-based nano-particles have gained popularity recently, it is essential to look at their appealing qualities. Superconducting quantum impedance device (SQUID), vibrating-test magnetometer (VSM) and electron paramagnetic reverberation (EPR) are some of the methods used. EPR is used to identify and differentiate between paramagnetic foci and free extremists in synthetic materials. Through cooperation with electrons in an example, it examines the real characteristics of attractive nano-particles and the influence of the external attractive field. VSM and SQUID, which have response qualities of 10-6 emu and 10-10 emu respectively, are used for very sensitive appealing estimates. Media such as powder, slender films and other powerful and fluid examples are shown using SQUID.

Interaction of biogenic nano-particles with environmental components

Biogenic nanoparticles (bio-NPs) more and more play a important position in strengthening plant resilience, specifically below drought pressure, via interacting with soil, plants and microbial groups. Before exploring their synergy with plant boom-promoting rhizobacteria (PGPR), it is important to recognise how those nanoparticles behave inside agroecosystems. When delivered into soil, biogenic NPs have interaction with soil minerals, organic remember and the rhizosphere environment, influencing nutrient mobilisation, soil structure and microbial dynamics. Several studies have proven that soil amendments

Table 2. Techniques for characterization of nanoparticles (29)

Technique	Characteristic
Atomic force microscopy (AFM)	Geometry, structure, distribution
Differential scanning calorimetry (DSC)	Thermal performance
Dynamic light scattering (DLS)	Hydrodynamic size distribution
Fluorescence spectroscopy	Optical properties
UV-VIS/Infrared spectroscopy	Structure, Functional group analysis
Mass spectrometry (MS)	Molecular weight, composition, surface
Nuclear magnetic resonance (NMR)	Structure, composition, purity
Scanning electron microscopy (SEM)	Aggregation, size and shape
Transmission electron microscopy (TEM)	Aggregation, size and shape
X-ray photoelectron spectroscopy (XPS)	Elemental and chemical composition

enriched with nanomaterials improve soil physical houses, decorate nutrient retention, restore soil fertility and in the long run make contributions to higher crop productivity (38). These interactions are driven by using the high surface place, reactivity and balance of biogenic NPs, which allow them to participate in various biogeochemical techniques.

A foremost problem with conventional soil amendments is the presence of antibiotic-resistant microorganisms, chemical residues and different contaminants that threaten soil health and meals protection (39, 40). Therefore, amendments should be ecologically secure, assist soil fertility and now not disrupt microbial ecosystems (41). In this context, biogenic NPs and PGPR are being explored as safer and more efficient options because of their biocompatibility and multifunctionality (42, 43). Biogenic NPs have verified the capability to reduce environmental stressors, beautify nutrient-use efficiency and beef up plant physiological responses, thereby contributing to progressed plant performance even beneath drought conditions (44).

Plant growth promoting rhizobacteria complement those features via both direct and oblique mechanisms. Direct mechanisms consist of nitrogen fixation, phosphate and potassium solubilisation and the synthesis of phytohormones which include indole-3-acetic acid (IAA) and siderophores, which together sell root improvement and nutrient acquisition. Indirect mechanisms involve the production of lytic enzymes, antimicrobial compounds and exopolysaccharides, in addition to pH modulation within the rhizosphere, which suppress soilborne pathogens and decorate soil aggregation. Numerous research has confirmed the capacity of PGPR to enhance plant growth and maintain soil fitness below both everyday and pressure conditions, consisting of drought (45).

The combined utility of biogenic NPs and PGPR has these days emerged as a promising technique in sustainable agriculture. Their interactions can make bigger fine results on soil nice, plant body structure and environment stability. Biogenic NPs can enhance PGPR colonisation, improve nutrient bioavailability and

toughen plant protection pathways, at the same time as PGPR can adjust NP conduct through altering their transformation, mobility and bioavailability within the rhizosphere (46). This synergistic dating contributes to step forward drought tolerance by retaining soil moisture, enhancing antioxidant protection and optimizing nutrient cycling. Fig. 2 depicts the interactive effects of nanoparticles (NPs) and plant growth-promoting rhizobacteria (PGPRs) on plants, soil and the broader environmental ecosystem. Nanoparticles enhance nutrient mobility, water uptake and activation of stress-response pathways, while PGPRs contribute phytohormones, siderophores, enzymes and nutrient-solubilising abilities. Together, they strengthen soil structure, promote healthier root systems and support beneficial microbial colonisation. Their combined action improves plant growth, resilience and soil biological activity, especially under stress conditions. The figure emphasises the synergistic potential of NP-PGPR integration in sustainable agriculture.

Upgrading soil quality through nano-particles and PGPR communications

It is portrayed from the perspective of those capabilities because soils perform a wide range of environmental functions. From the perspectives of climate and simultaneous farming, it is described as "the limit of a dirt to work inside biological system and land-use limits to support natural efficiency, keep up with ecological quality and advance plant and animal wellbeing" (47). The super substance components of soil quality are pH, soil natural matter and open macronutrients (nitrogen, phosphorus and potassium). On the other hand, the most widely used actual indicators are mass thickness, primary solidity and water retention, while the most widely used organic markers are nitrogen mineralisation, microbial biomass, soil breath and extracellular enzymatic exercises (48). In view of these limitations, this audit will evaluate the dedication of co-applying NPs and PGPR to improve soil quality. Co-applying NPs and various PGPRs has been suggested as a workable solution to address the issue of improving soil quality. The presence of NPs may increase PGPR production because they provide a substrate with a large surface area and

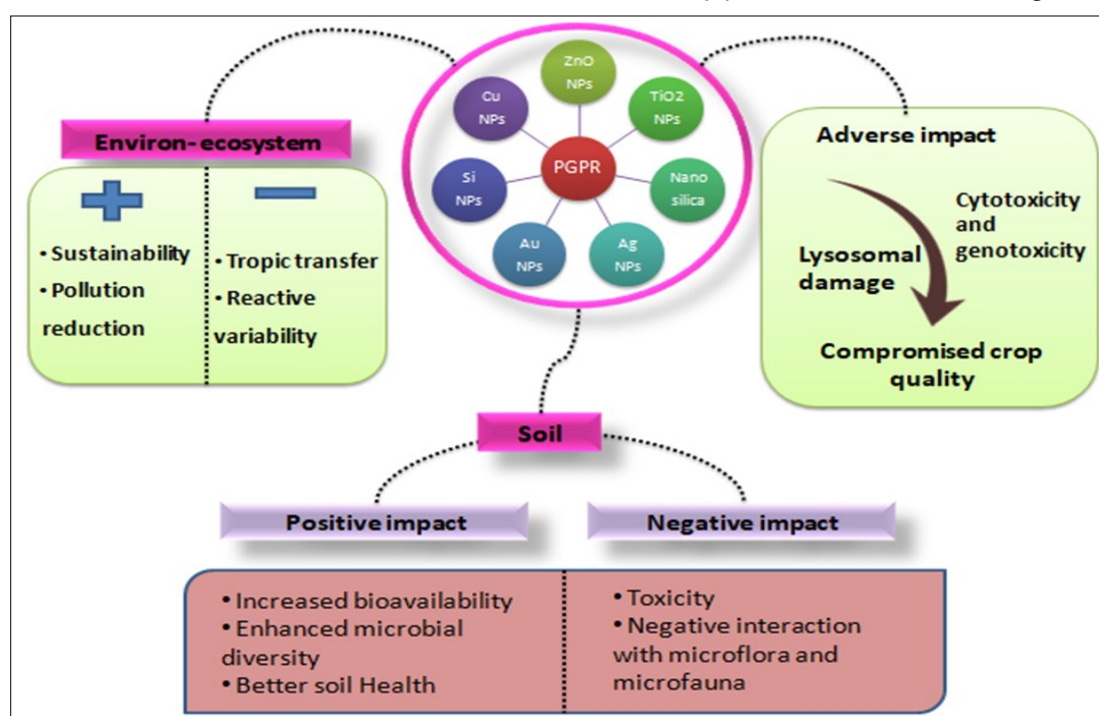


Fig. 2. Interactive effects of NPs and PGPRs on plant, soil and enviro-ecosystems.

increased sustenance for their endurance (49, 50).

Supplement upgrade in soil: the job of nano-particles and PGPR

Numerous demonstrations described the physical, material and organic characteristics of soil and examined the impact of co-applying PGPR and NPs on soil quality. When compared to applying NPs or PGPRs alone, it is often observed that applying both together improves the amount of mineral supplement content in rhizospheric soils (50). In comparison to a single amount of nitrogen, the combined use of NPs and PGPRs resulted in increased soil nitrate levels. In any event, as compared to normal plants, PGPR and NPs enhanced the accessibility of natural carbon, phosphorus and nitrogen. Due to their conservative nature and inherent use, nano-particles were sprayed on plant leaves at low concentrations (51). The employment of NPs as nano-development controllers to work on plant development and advancement sparked extra interest from plant physiologists. This is mostly because of the NPs' potent stock, collection and transportation of necessary minerals (52). They decompose quickly when mixed with soil due to disintegration and degradation influenced by soil characteristics and organism activity. PGPR accelerates the aggregation of mineral supplements from NPs, especially those that solubilise natural phosphate.

By combining PGPR with NPs, soil microorganisms are able to focus on the uptake of other essential elements without having to look for particular supplements. This change enhances chemical activity and facilitates the addition of additional supplements, leading to a more secure supplement interaction and, in general, an improvement in soil ripeness (51, 53).

Further developing soil water maintenance with nanoparticles and PGPR

NPs, especially those with coarse surfaces, may increase the water-holding capacity (WHC) of soil because to their increased surface region to volume proportion. Additionally, under various conditions of the tests evaluating the co-use of NPs and PGPR, the beneficial effect of NPs on the water maintenance limit has been discovered. The combined use of PGPR and NPs improved the soil's water holding capacity (WHC) as opposed to applying them separately (49, 54). Although a single application of PGPR has never been shown to increase soil WHC and water content, it can increase plants' resistance to water scarcity.

However, given the supplement cycling, degradation of soil natural matter and microbial flagging in light of increased soil dampness levels, enhanced WHC through the application of NPs works in concert with PGPR (55). It should be noted that the PGPR application of NPs currently appears to be unable to lead to their aberrant meaning.

Tweaking soil microbial networks

The ability of native soil microbial populations is eventually enhanced by nanoparticles, which improve several physicochemical characteristics of soil. NPs can improve microbial biomass, overflow and expansion by supporting WHC, soil pH, substrate and supplement accessibility. Furthermore, it has been demonstrated that NPs increase the typical rhizobia's nodulation with vegetable plants. This is because to NPs' enhanced air circulation, which allows tiny microorganisms to enter more air. These microorganisms may survive on the NPs' porous surface for a considerable amount of time before colonizing the roots (56).

PGPR and nanoparticles: a complementary strategy to counteract environmental stressors

Crops must be able to grow with more nutritional content, reduced concentrations of pesticides and disease resistance in order for agriculture to be sustainable. Over the past few decades, the extensive use of costly agrochemicals in agriculture has prompted the creation of more ecologically friendly substitutes, such as PGPR and NPs (55). Because of their substantial effects on plants, PGPR and NPs have received a lot of attention. In recent years, however, the combination of PGPR and NPs has shown more effective in plant production than either one alone. Numerous research have confirmed the important effect PGPR and NPs have in raising agricultural production.

Similarly, compared to PGPR alone, the combination of *Alcaligenes* sp. and NPs increased fresh and dry mass, plant length, yield and fruit quality. In order to reduce greenhouse gas emissions related to the manufacture of ammoniac fertilisers and their volatilisation have also investigated PGPRs with NPs during times when fertiliser frequency is reduced. NPs, *Enterobacter*, *Pseudomonas*, *Azospirillum* and *Agrobacterium* were used to increase the production of sustainable agriculture. The frequency of seed germination, plant height, dry-fresh biomass and agricultural production may all be less affected by the combined use of PGPR and NPs than by their use alone. This combo can achieve several objectives. Improved plant performance and productivity are a direct result of the PGPR's regular production of plant hormones like indole acetic acid and siderophores, as well as the increased availability of soil minerals through phosphate solubilization and N₂ fixation. NPs can increase the PGPR's efficiency and eventually, plant output in addition to giving it nutrient-rich substrate and assisting in its survival in larger numbers.

The PGPR is known to lessen a number of environmental stressors that impede the growth and development of plants. Numerous studies have shown how well they work to counteract heavy metal pollution, low and high light intensities, salt, drought, soil flooding and nutritional imbalance. By using PGPR's capacity to release exopolysaccharides under arid conditions, plants can effectively establish stress tolerance (55, 56). It promotes water absorption in saline conditions, boosts potassium accumulation at the expense of sodium, minimizes the direct detrimental effects of soil salinity and increases the activities of antioxidant enzymes. All of these changes promote plant development in salty conditions. Similarly, the PGPR has been shown to both enhance the absorption of nutrients overall and immobilize and limit the uptake of heavy metals by plants, which lowers the toxicity of heavy metals. When combined with Ag-NPs, *Bacillus pumilus* outperformed other bacteria in terms of stimulating the development of onion plants. The combination treatment lowered the salt-induced retention of moisture in rhizospheric soil and while leaf flavonoids dropped, the protein content of the bulb rose. Ag-NPs increased amounts of proline and sugar. Although *Bacillus pumilus* was shown to be more significant in growing agronomic responses under control settings, *Pseudomonas moraviensis* may have acclimated to saline environments.

Furthermore, it has been shown that NPs improve drought stress, increase salt tolerance and lessen the toxicity of both organic and inorganic soil pollutants to plants. NPs-amended soils benefit from drought stress due to their increased water-holding

capacity and high surface area-to-volume ratio. Plants in soil modified with NPs also lessen soil saline conditions because of the lowered osmotic stress, which raised soil water content and the transitory binding of Na^+ on the sorption sites of NPs. The main way that NPs reduce toxicity stress is by the sorption of both organic and inorganic heavy metals. Numerous researches have looked at all of these NP uses against different environmental stresses. The prospect of combining PGPR and NPs to improve the environmental conditions for plant development has recently been investigated in various researches, assuming that the two additions would work in concert. These research have actively investigated PGPR and NP synergies. Fig. 3 demonstrates how PGPRs and nanoparticles collectively enhance crop productivity through complementary mechanisms. PGPRs improve plant growth by producing hormones, fixing nitrogen and generating stress-alleviating metabolites, while nanoparticles boost nutrient-use efficiency and activate antioxidant and defense pathways. This combined influence increases photosynthetic efficiency, biomass production and tolerance to drought and other abiotic stresses. Their synergistic effects contribute to healthier plant physiology and increased crop yield. The Figure highlights the promise of NP-PGPR technologies as advanced tools for improving agricultural performance.

Application of microbial biotechnology in improving drought spell resilience

Plant boom is becoming higher. Rhizobacteria (PGPR) and mycorrhizae, important ingredients of the soil microbiome, are well-sized for his or her contribution to improving plant increase and fitness; they offer a unique and powerful alternative for compound manures in agriculture, underscoring their relevance in modern agronomic practices (57, 58). Mycorrhizae, specifically arbuscular mycorrhizal fungi (AMF), are famous for assisting flowers in growing and making them more resistant to both residing and nonliving stressors. This is basically achieved by way of making it easier for flowers to absorb nutrients, especially phosphorus, which is crucial for his or her boom. Mycorrhizal infection has been established to have a huge effect on how flora get minerals, taking part in development via supporting the parasite to get the nutrients it needs.

Moreover, mycorrhizae can influence advancements in plant defense research by providing a natural barrier against microorganisms and herbivores, but to a lesser extent than direct responses to these threats. Furthermore, PGPR plays a key role in advancing plant mineral sustenance, which suggests that they might be used as biofertilizers. The proportionate quality ratio between these bacteria and plants during colonisation, which shows a synergistic communication that benefits plant growth, is closely linked to the successful use of PGPR in farming (59). PGPR has been shown to have both direct and indirect positive effects on plant health, including increasing the accessibility of supplements and providing phytohormones and other growth-promoting agents. By increasing microbial activity and soil component accessibility, the introduction of PGPR and mycorrhiza into supplement-unlucky soils has improved soil quality and promoted plant growth (60).

Additionally, the use of these microbes has been linked to modifications in the essential and auxiliary metabolome of the plant, which enhances growth and production. In essence, PGPR inhibits plant diseases and directly promotes plant health by increasing nutrient availability and acting as a phyto stimulant. Factors such as yield genotype and the existence of harmonious growths might influence the complex collaboration between PGPR and plants. This complexity emphasizes how astounding their interactions with plants are. Additionally, it has been suggested that PGPR be used to restore soil fertility by exploiting the nitrogen-fixing abilities of certain microbes within this community (60). Nevertheless, mycorrhizae play a vital role in increasing supplement retention, integrating plant growth compounds and improving plant defense against dry season stress, all of which increase plant adaptability to environmental challenges. Compared to traditional treatment methods, mycorrhizae and PGPR have been suggested as environmentally benign alternatives that may result in reduced ecological impact and the production of biofuel (61). In summary, both PGPR and mycorrhizae are invaluable in sustainable agriculture, providing a range of benefits from enhancing plant growth and supplement uptake to strengthening resistance to biotic and abiotic stressors. As soil quality enhancers and biofertilisers, they serve as essential tools in the pursuit of cost-effective and environmentally friendly agricultural methods. Numerous studies have highlighted the various roles that

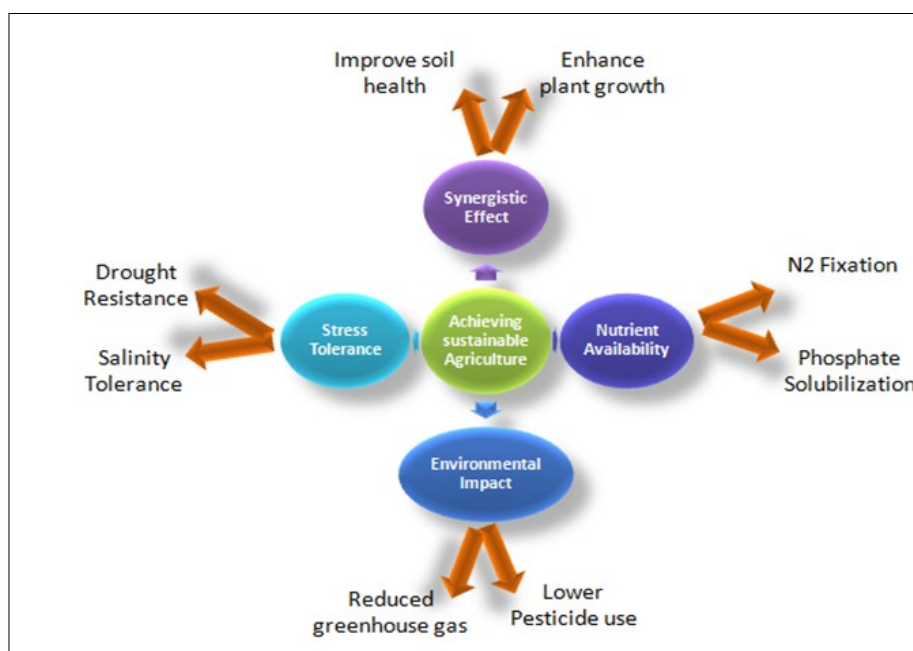


Fig. 3. Enhancing crop productivity with PGPR and NPs.

mycorrhizae and plant development-advancing rhizobacteria (PGPR) play in enhancing dry season tolerance in various plant species. As the trial approaches, these tests encompass a variety of plant and animal categories. Overall, they highlight how mycorrhizae and PGPR contribute to increased dry season adaptability by elements such as modifying workouts for cancer preventive agents, improving supplement and water absorption and modifying physiological and biochemical processes.

Challenges and future perspectives

A complex and multifaceted test is presented by the current landscape of biotechnological mediations for improving crop dry period resilience. Understanding how plants respond to dry spell pressure at the subatomic and whole harvest levels has advanced significantly, but the task remains challenging due to the co-occurrence of several abiotic stressors, such as high temperatures, high radiation and a lack of supplements. A key component of this effort is developing dry season safe assortments using traditional raising techniques enhanced by biotechnological tools, such as identifying dry spell safe traits, QTL analysis, quality modification and marker-assisted determination. Biotechnology plays an increasingly important role in improving plant resistance to dry spell pressure, much as the necessity to cultivate crops that can withstand harsh environmental conditions. One of the main goals of plant biotechnology is to build plants with increased tolerance to abiotic challenges, such as the dry season. This is anticipated to have commercial uses in the near future. However, the complexity of local pressure reactions in plants makes it difficult to design these features (62).

Recent research has focused on exposing novel practices and anticipated increases in pressure on plant executives during the dry season. The role that microRNAs (miRNAs) play in improving the dry season resilience of plants presents a promising avenue for further research, particularly in the development of grain crops that are resistant to dry spells. Additionally, using silicon has demonstrated promise in improving rice plants' water status, photosynthesis and retention of mineral supplements under the stress of the dry season, suggesting an additional method to lessen the strain of the dry period on plants.

Additionally, emerging research is linking subatomic responses in dry spell-focused plant settings to broader environmental contexts, such as three-sided species cooperation and the nature of bug-communicated microorganisms. This is particularly relevant during times of environmental change. An additional fundamental area comprehends how plant chemicals affect dry spell pressure responses and phytohormonal relationships, with the potential to regulate phytohormones to increase plant resistance to the dry season. Furthermore, directing the growth and improvement of food crops under these pressure circumstances is crucial for future climatic change, as is broadening the study of plant responses to combined high temperature and dry season pressure. Innovative techniques, such as using sonic emanations to estimate cavitations in plants triggered by the dry season, are opening up new avenues for investigation and may broaden our understanding of dry period resistance and recovery capabilities. Additionally, studies that focus on how dry spell weight affects a plant's susceptibility to herbivore colonisation-for instance, in *Solanum lycopersicum*-provide insight into the complex interactions between dry season pressure and plant-herbivore relationships, which is important for comprehending the biological effects of dry spell pressure (63).

Overall, planning these diverse tests demonstrates the anticipated advancements and future research directions in plant dry spell pressure. Among these are the study of miRNAs, silicon application, relationships between plants, vectors and microorganisms, phytohormonal responses, the challenges of combining high temperatures and dry spell pressure, new methods for focusing on dry season resilience and the biological effects of dry season weight on plant-bug cooperation. This multifaceted approach, which combines traditional and biotechnology methods, is essential for advancing our understanding and managing crop dry season stress (61).

Conclusion

Drought is a main abiotic strain that severely reduces global crop productiveness by using proscribing water availability, hindering nutrient transport and suppressing photosynthesis, in the end affecting each vegetative and reproductive levels. While traditional treatments which include silicon, selenium, hormones and osmo protectants provide partial alleviation, their effectiveness declines under intense water shortage. Biogenic nanoparticles provide an extra superior and centered solution because of their excessive reactivity, managed release and capacity to regulate key physiological and biochemical strategies. They enhance water retention, nutrient-use efficiency and antioxidant activity while minimizing osmotic and oxidative stress. An emerging advancement is the blended use of biogenic nanoparticles with plant boom-selling rhizobacteria (PGPR). This synergy strengthens root-soil interactions, improves nutrient mobility, enhances osmo protectant accumulation and fosters a more resilient rhizosphere. Although promising, demanding situations along with inconsistent NP synthesis, unknown environmental affects and absence of regulatory standards have to be addressed to make certain safe, powerful and sustainable drought management strategies.

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Authors' contributions

All authors played an important role in the preparation and publication of this manuscript. All authors read and approved the final manuscript.

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