https://doi.org/10.33472/AFJBS.6.5.2024. 7858-7876

AfricanJournalofBiological Sciences

Understanding Metal-Based Nanoparticles in Agricultural Ecosystems for Sustainable Growth: Nano Farming

Sushma Shree Krishnappa[1]; Shankramma Kalikeri*[1]; Charan Kumar Kachintaya[2];and Lingaraj Honnuru Gavisiddappa[3]

[1*]Division of Nanoscience and Technology, School of Lifescience, JSS Academy of Higher Education and Research Sri Shivarathreeshwara Nagara, Mysuru – 570 015 Karnataka, India.
[2] #9A, Shankar Colony I Cross, SN Pet, Ballari - 583101, India
[3]Department of Environmental Science, School of Lifesciences, JSS Academy of Higher Education Research, Sri Shivarathreeshwara Nagara, Mysuru-570015, Karnataka, India
***Corresponding author Email**: shankrutk@jssuni.edu.in

Article History
Volume 6, Issue 5, 2024
Received: 22 May 2024
Accepted: 29 May 2024
doi:*10.33472/AFJBS.6.5.2024. 7858-7876*

Abstract:

Nanotechnology has gained substantial attention in agriculture, notably with the introduction of metal-based nanoparticles (MB NPs), which have the potential to alter farming techniques. However, as their use increases, it is critical to understand their behavior in soil environments to assess their impact on agricultural ecosystems and assure sustainable practices. The aggregation or dispersion of MB NPs in soil has a significant impact on their mobility and bioavailability to plants and soil organisms, with pH, ionic strength, and chemical composition all playing important roles. Furthermore, the interaction of MB NPs with soil-dissolved organic matter affects their stability, reactivity, and plant absorption capability. Hetero aggregation with inorganic colloids influences the distribution and availability of MB NPs in the soil matrix, as well as their transit within agricultural soil. Dissolution, oxidation, and reduction alter the physicochemical properties of MB NPs in agricultural soil, which may affect their toxicity to soil organisms and plants. Comprehensive study in this field is required to ensure the safe and successful use of metal-based nanoparticles in modern agricultural methods.

Keywords: Nanotechnology, Metal-based nanoparticles, Crop improvement, and Sustainability.

Introduction:

Soil is essential to a healthy ecosystem because it provides a home for several processes that help plants and animals adapt to changing environmental conditions or reduce their effects. Many technological advancements have been made to improve soil health or boost the productivity of damaged soils, but they haven't been able to restore or improve soil health to the required levels because they are pricy, practically impractical, or, to a lesser extent, labour-intensive(1). A rise in biotic and abiotic stressors will surely follow future unfavourable agroclimatic conditions, and this will have a significant effect on soil health and agricultural productivity (2).Nanotechnology has been a hot topic in agriculture, as metal-based NPs have attracted interest for theirpotential to revolutionize farming practices. However, as the usage of these nanomaterials increases, it is critical to understand their behavior in the soil environment to assess their impact on agricultural ecosystems and assure sustainable practices. One of the primary aspects of the behavior of metal-based NPs in agricultural soil is their inclination to aggregate or disperse(3). The balance between aggregation and dispersion, which is determined by soil properties such as pH, ionic strength, and the presence of other chemicals, affects the mobility and bioavailability of NPs to plants and soil organisms.Due to their improved physical, chemical, and biological characteristics nano materials and to maximising these nanomaterials' positive attributes for agriculture, careful management will also reduce any potential negative effects on soil health and the environment. It is necessary to conduct in-depth study in this area to ensure the appropriate and efficient use of metal-based NPs in modern agricultural practices (4).

Plants as key component in agriculture practice also shown complexed and dynamic interactions with metal-based NPs. The stability, aggregation, transport, interaction with plants, bioavailability, toxicity, and destiny of NPs in ecosystems have all been the topic of several reviews that have been published(5). The stability, transformation, transport, and interactions of metal-based NPs with plants in agricultural plant and soil systems are discussed in this review, along with current research and future directions.

Behaviour and interaction of MB NPs.

MB NPs have special chemical and physical properties, to boost their effectiveness, these are usually made with properties, such as chemical composition, unique system, surface coating, and surface functionality.Agricultural soil contains a lot of Dissolved Organic Matter (DOM), DOM is the one of the most reactive and mobile soil organic components, significantly affects and influences the aggregation of MB NPs in the soil matrix (6). Through a variety of interactions, DOM often modifies the ambient behaviour of MB NPs. Vander Waals forces, hydrophobic contact between DOM and NPs surfaces, and electrostatic interaction are all important aspects of the interaction process. DOM typically prevents NP aggregation by enhancing hydrophobicity or electrostatic stability on the surface of the particles (7)**.** Due to the fact that both the surface charge on NP and the soil colloid surface depend on pH, pH plays a significant role in determining Heter aggregation(8) . (9) conducted to investigatethe hybridization of gold nanoparticles (Cit-AuNPs) with hematite (-Fe_2O_3) colloids. According to their findings, Cit-AuNPs are capable of destabilizing hematite by an "Electrostatic patch mechanism" at pH levels where Cit-AuNPs and hematite are oppositely charged. these pH values are those where soil organic matter is absent. Theoretically, these alterations can offer surface attachment resistance and steric stabilization to lessen the tendency for particle aggregation.MBNPs environmental toxicity and reactivity are key factors in the dynamic process of breakdown. The inherent qualities of the individual particles as well as the matrix of the media they are surrounded by affect both solubility and dissolution rate.

Chemical transformations

The physical and chemical properties of soil significantly influence soil health and quality. Figure 1 illustrates how MB NPs can undergo chemical transformations in agricultural soil, such as reduction or oxidation. These reactions are linked processes in natural systems that entail the transfer of electrons across chemical moieties (10). The oxidation state, creation of reactive oxygen species, persistence, and other chemical transformation processes of MB NPs may all be significantly impacted by sunlight-induced redox reactions. In natural systems, these processes are interrelated and entail the transfer of electrons to and from various chemical moieties. It is well known that a variety of MB NPs, such as iron, gold, and silver NPs, are active in reduction or oxidation reactions. Redox reactions brought on by sunlight have a significant role in these NPs oxidation states, production of reactive oxygen species, and environmental persistence.

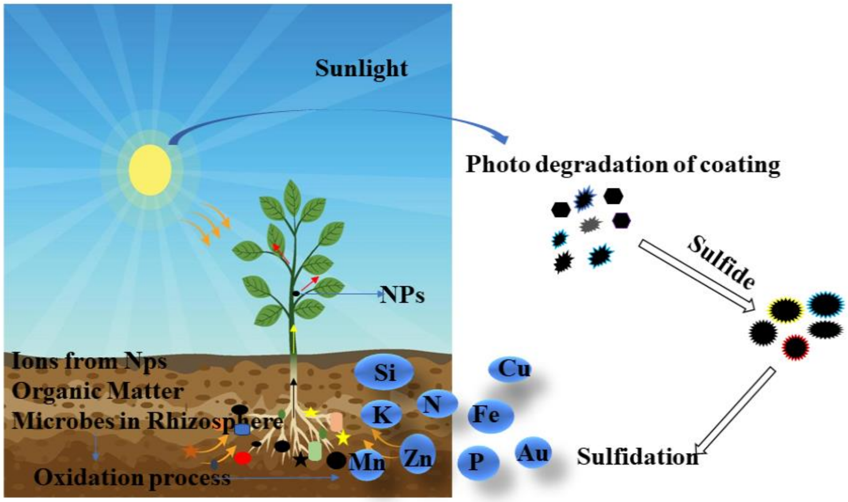

Figure 1. Chemical changes caused by MB NPs in agricultural soil.

Uptake and translocation ofMB NPs insoil.

The bioavailability of MB NPs is determined by a sequence of bio/geo reactions that take place in the soil. After interacting with plant roots, the NPs translocate to aerial parts and accumulate in cellular or subcellular organelles. Figure 2 shows how plant uptakes and translocate NPs from the soil, NPs may enter mature plants either by the roots or by the aboveground part of the plant. In fact, the aboveground part of the plant is naturally exposed to the nanoparticles in the atmosphere and artificial exposure can occur during the spraying or direct injection of them into the leaf(11). However, there is a cuticle on the surface of the plant, which is a natural barrier. It is a complex membrane with a number of important protective functions which are based on ensuring impermeability to most substances(12) . Two different uptake pathways are likely to occur: a polar pathway, through the leaf surface polar apertures, e.g., trichomes, hydathodes, necrosis spots and stomata, as well as a nonpolar pathway, through the leaf cuticle and its pores, which have a size of 0.2–2 nm. The only proven way that has been performed is for the NPs to enter the plants through the stomata(13).

Once the NPs enter the plant, there are two ways that they can move through the tissues: an apoplastic and a symplastic transport. Apoplastic transport takes place outside the plasma membrane, through the cell walls of neighbouring cells, and extracellular spaces and xylem vessels are what allow nanomaterials to reach the conductive tissues for further upward movement towards the photosynthetic parts of the plant (12). The apoplastic pathway is important for radial movement in plant tissues and the central cylinder, as well as vascular bundles, in the phloem are what allow the distribution towards the tissues and organs in the roots (14). It was also described that the particles outperform the epidermal and cortical cells by using apoplastic transport until they reach the endodermis. However, NPs can form aggregates and accumulate in the endodermis due to the presence of Caspary strips, which act as a resistant barrier. For efficient translocation to shoots, the NPs must then pass into the symplast (15). Symplastic transport involves the movement of water and substances between the cytoplasm of the neighbouring cells by using plasmodesmata and retina structures (14). The effective translocation of the nanomaterials to the shoots is possible after their transfer to the symplast, thus, symplastic transport is considered more important for the transport of NPs. NPs enter the intracellular space in several ways. It is possible for them to pass through by binding themselves to transport proteins, through ion channels, aquaporins, endocytosis or through the initiated formation of new pores, which may be larger than the originals (16). The processes of the adsorption, translocation and accumulation of NPs depend significantly on the type of plant but also on the physical and chemical nature of the nanoparticles themselves (17). The transport of NPs in a sympathetic way across the membrane, and their accumulation results in an effect on the charge inside the cell, which subsequently changes the electrochemical potential of the membrane. Any changes in the electrochemical potential can affect the transport of other materials across the membrane. The electrochemical potential of the membrane should remain in equilibrium to maintain the turgor pressure, water and nutrient uptake and plant growth (18). Among the important factors affecting accumulation were the crystallinity of the used NPs (19), the hydrodynamic dimensions (20), the character of the ambient soil, e.g., its “organic” or inorganic character and/or the effect of zeta potentials of the NPs (21)

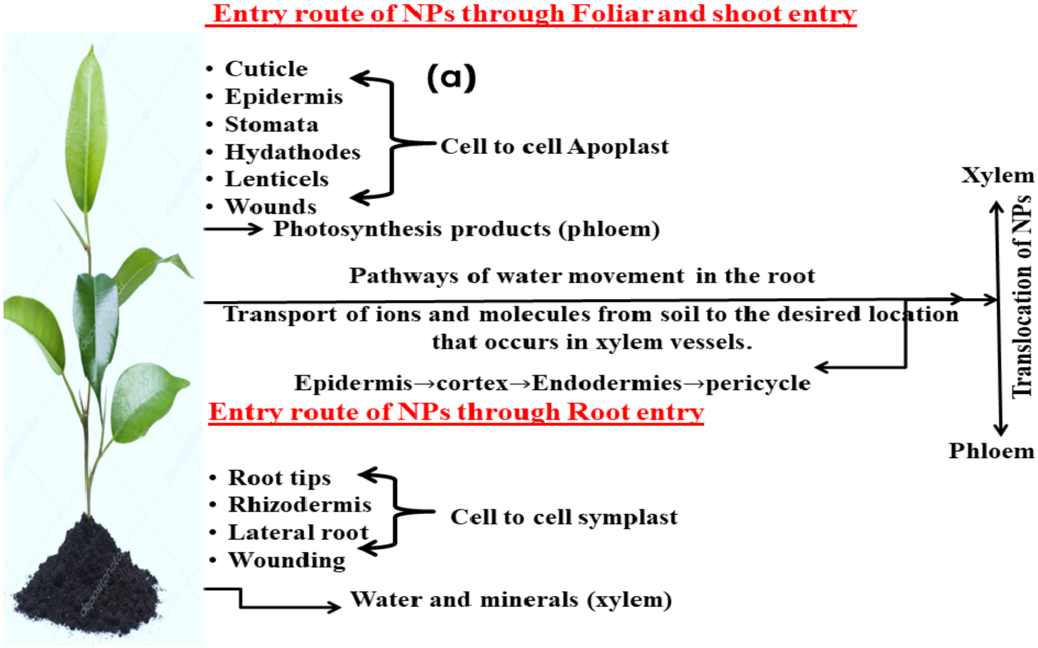

Figure 2 Graphical representation of NPs uptake through different routes and their translocation pathways in different plant (1).

Physiological and biochemical effects of MB NPs on plant.

The most prevalent species in the environment, plants, are most likely to be affected by NPs in a good or negative way. The presence of NPs in the air, water, and soil shows inevitable effects on plants(22) . NPs are absorbed by rootless or rooted surfaces either directly or indirectly through a variety of physical and chemical mechanisms. By modifying the enzymatic activity involved in the C3 cycle and controlling photosynthetic pigments that are essential for plant development, nanotechnology can improve the physiological process of photosynthesis in plants(23). The influence of nanomaterials (NMs) on crop mineral nutrition, enzyme activity, and electron transport systems affects crop development and physiology in both positive and negative ways. NPs have been shown to enhance germination and stimulate seedling growth, possibly because of better xylem humidity, water transfer, and nutrient delivery (24).NPs increase antioxidant activity, which can promote plant development under drought stress, and enhance the absorption of water and nutrients while lowering the generation of dangerous free radicals(25). Transcriptomic and proteomic approaches have deeply investigated the effects of NPs on different plant species at the molecular levelbecause of their non-threatening use in the agriculture sector, as seen in table -1, a variety of NPs, including Titanium Dioxide (TiO_2), Iron Oxide (Fe_3O_4), Zinc Oxide (ZnO), Silicon Oxide (SiO_2), copper (Cu), and selenium (Se), have attracted a lot of interest recently(26). NMs is used as nanofertilizers to lessen nitrogen losses due to leaching and emissions by soil inhabitant microorganism. There is a linkage between nano fertilizers and soils that produce nano particles to overcome the problems of leaching (27). This efficiency can be increased by delivering fertilizer at a targeted site and avoid detoxification of soil. Reducing the loss of applied fertilizer can also increases crop productivity, and increased seed germination, plant growth and agronomic yields at a small dose, leading to significant economic and environmental benefits (28).

Table1: MBNPs for agriculture practices.

Metal NPs	**Plant**	**Size and concertation**	**Beneficial effect**	**Reference**
ZnO, Ag, CuO and TiO_2	Onion	16-50 nm (ZnO), 50-100 nm (Ag), 60-150 nm (CuO) and 100-120 (TiO_2)), 750, 1000, 1250 and 1500 mg kg^1 respectively	Increase the level of IAA in roots	(29)
MgONPs	Tobacco	50nm 50–250 µg/mL in matrix media	The chlorophyll structure and improved responds of the plant growth	(30)
$NSiO_2$	Strawberry	220 nm (0, 25 or 50 mM NaCl)	Increases the shoot dry weight and proline content	(31)
SiO_2 and TiO_2	Wheat	- 0, 500, 1000 and 2000 mg L^{-1}	It may regulate plant growth and play a role like plant hormones.	(32)
	Pea	0 and 50 mg/L	significantly affected the germination rate (GR) daily germination (MDG)	(33)
	wheat	4 different types of soil with sandy to clayey.	No sign of acute phytotoxicity has been detected in growth, biomass, chlorophyll content.	(34)
	Wheat	0.01%, 0.02%, and 0.03%	Titanium dioxide nanoparticles at 0.02% increased almost all agronomic traits seed weight, final yield, biomass, harvest index, gluten, and starch contents.	(35)
	Wheat	347–447 nm 40 mg L^{-1} and 40 mg L^{-1} ppm calcium phosphate on plants	Changes the calcium performs	

				(36)
Fe_2O_3	Maize	53nm 0, 10, 100 and 1000 mg -^{1}	The improves the growth of Fe_3O_4 NP-treated maize can be attributed to the balance of the plant redox system brought about by higher ferritin.	(37)
	Tomato	50,100,200,400,800 mg L^{-1}.	The Fe_2O_3 Nps increases the seed germination and root, shoot length of s. *lycopersicum*	(38)
CuO	Rice	22nm Hydroponic condition,62.5, 125, and 250 mg L^{-1}	Increases the fresh weight of the rice seedlings.	(39)
	Electron paramagnetic resonance (EPR)	In vitro studies	SulfidatedCuO continues to generate some ROS activity due to the release of free copper by H2O2 oxidation during the Fenton-chemistry-based EPR assay.	(40)
SWCNTs	Soybean	- 0, -0.3, -0.6 with PEG 6000.	Enhanced the water uptake	(41)
Ag/ZnO	Wheat	20nm 100 mg L^{-1}	Enhanced gas exchange capacity and photosynthetic carbon assimilation	(42)
ZnO	Maize	100 mg L^{-1}	The activities the UDP-glucose pyro phosphorylase, phosphoglucoisomerase and cytoplasmic invertase by 17.8%, 391.5% and 126%	(43)
	Eggplant	Foliar spray 50 and 100 mg L^{-1}	Enhance the restoration of the photosynthetic efficiency	(44)
SeNPs	Carrot	Combining with glycine betaine and proline under wastewater treatment.	Increased free proline contents, total phenols, superoxide dismutase, catalase,and hydrogen peroxide throughout the two growth stages.	(45)
	Soybean	AsIII (25 μmol/L) and10	Increasesthe soybean dry weight	(46)

		and 25 μmol/L at the V2 growth stage.	and roots parameters under asIII stress.	

Nanoparticles of ZnO, Ag, CuO and TiO_2 were treated with different concentrations of 750, 1000, 1250 and 1500 mg kg^{-1} had significantly outperformed control in terms of germination, shoot length, root length and vigour index.Ag NPs @ 1000 mg kg-1 (69%) and TiO_2 at the 750 mg kg^{-1}62 % germination, seedling vigor and, CuO at 60% germination. ZnO NPs @ 1000 mg kg-1 had the highest germination of could increase the level of IAA in roots, which in turn can increase growth rate of seedlings. The quenching of free radicals by NPs that entered through fractures in the seed coat and reached into free radicals, which resulted in higher seed vigor, might be linked to improved physiological parameters. The beneficial effect of the ZnO NPs in improving the germination could be ascribed to higher precursor activity of nanoscale zinc in auxin production.(29).

Cai et al (2018) studied the effect of MgONPs on the different morpho-physiological changes in tobacco plants grown in matrix media at a concentration of 50–250 μL^{-1}. The seeds did not show any toxicological consequences at this concentration, even though there was no noticeably higher germination rate when the plants were exposed to 250 g/mL MgONPs. Chlorophyll a and b contents were significantly raised by the MgO NPs, going from 0.21 and 0.12 g/g to 1.21 and 0.67 g/g, respectively. MgO likely operates in the chlorophyll structure, which may be the main factor in the better responses of the plant treated with the MgONPs.In this work, we put out the hypothesis that the addition of low concentrations of MgONPs might promote the growth rates of the tobacco plants in a synergistic manner and perhaps improve their photosynthetic efficiency(30)

Avestan et al (2019) described how strawberry plants react to salt stress (0, 25 or 50 mM NaCl) and nano-silicon dioxide treatments(0, 50 and 100 mg L-1). Strawberry plants which received 100 mg L^{-1} $nSiO_2$ before the flowering stage and 50 mg L^{-1} thereafter (Si_6) showed the highest fresh shoot weight (41.2 g), while the highest shoot dry weight (13 g) and greater proline content was recorded for plants which received 100 mg L^{-1} $nSiO_2$ before flowering and 50 mg L^{-1} thereafter (Si_6) or plants that received 50 mgL^{-1} $nSiO_2$ before flowering stage (Si_3). The NaCl salt treatment reduced fruit output by 61%, resulting in the lowest fruit yield being seen in 50mMNacl as compared to control. When comparing strawberry plants treated with salt treatments without nano-silicon dioxide treatment, NSiO2 treatment resulted in a substantial drop in proline concentration in salt stress plants. A negative association (−0.63058 **; $p < 0.01$) was found between proline concentration and EWL(31).

Faraji and Sepehri (2019)study the effects of sodium nitroprusside (SNP) and TiO_2NPs (0, 500, 1000, and 2000 mgL^{-1}) as NO donors on wheat seed germination and seedling development under polyethylene glycol (PEG)induced drought stress. Wheat seed germination and seedling development were increased by the administration of TiO_2 NPs alone or in combination with SNP treatments under both normal and stressful conditions(32).

Basahi, M. (2021) explained the positive and/or negative impacts of nanoparticles can be established in pea seed. Treatment of pea seeds with TiO_2 induces embryonic axis biomass by 10% after 5 days of germination with 50 mg/L TiO_2, delay in pea seed germination, embryo development, and water supply. The variation in the solute leakage of pea seeds during germination after soaking with 50 mg. L-^{1} TiO_2 can be attributed to a disorder in nutrient supply(33).

Larue et al., (2018) reported that in wheat plants treated with TiO_2 NPs, increased development of the roots and shoots has been noted. the capacity to trigger plant cell division and cellular development suggests that TiO_2 NPs may control plant growth and have a similar function to plant hormones like cytokinin and gibberellin (34).

Mustafa et al., (2021) was studied to assess how wheat under drought stress responds to calcium phosphate and TiO_2 NPs. The greatest outcomes came from applying 40 ppm TiO_2 NPs and 40 ppm calcium phosphate to plants together. In comparison to control, they enhanced the length of the wheat's roots (33%), shoots (53%), fresh weight (48%), and dry weight (44%). TiO_2 strong surface reactivity causes them to either build new holes or enlarge existing ones in the roots, which improves nutrient and water movement inside the plants and promotes growth and development even under unfavourable circumstances. In plants, calcium plays the secondary messenger function by controlling the expression of increased indole acetic acid and gibberellin production, as seen in wheat. They control the normal operation of many mechanisms and modulate the osmotic pressure(35). TiO_2 NPs with calcium phosphate improved the absorption of potassium, phosphorus, and nitrogen in wheat. The technique entails the sequestration of nutrients by nanoparticles, and they serve as a stock that provides sufficient nutrients to plant roots. They improved plants' capacity to absorb and use water and nutrients from the soil(36).

Mahboobeh Jalali et al., (2016) studiedthe maize plants (Zea mays L. cv. Merit) grown in calcareous soil were foliar-sprayed with or without 100 mg Fe g–1 in the forms of Fe3O4 nanoparticles (NPs) and ethylene diamine-N,N-bis(2-hydroxyphenylacetic acid) Fe sodium complex (Fe-EDDHA), at different growth stages. Iron treatments improved maize photosynthesis and hydrogen peroxide and superoxide anion scavenging capacity and lowered the rate of membrane lipid peroxidation. Iron treatment also accelerated vegetative growth and caused earlier entrance to the generative phase. Differences between ameliorative effects of Fe-EDDHA and Fe3O4 NPs were particularly noticeable in the generative growth phase. Improvement of calcium, Fe2+, total Fe, and ferritin contents were more pronounced in Fe_3O_4 NPs treatments (164%, 200%, 300%, and 200% of the control, respectively)(37). Shankramma et al.,(2015)shown that the application of Fe_2O_3 NPs increased the length and fresh and dry weight of the shoot and root in tomato plants(38).

Yang et al., (2020) described the phenotypic alterations brought on by brief contact with CuO NPs in hydroponic rice seedlings at an early stage. Comparing the exposed seedlings to the control plants, phenotypic alterations were seen in the plants subjected to concentrations of 62.5, 125, and 250 mg CuO NPs. Particularly, the rice plants' roots and shoots were shorter than those in the control, indicating that CuO NPs were hazardous to them(39)In comparison to the control, the plants treated with suspensions of 250 mg/L CuO NP showed no discernible phenotypic alterations and changes in the fresh weight of the rice seedlings. In aqueous solutions, it has been discovered that CuO NPs may release Cu ions, which may play a role in the toxicity of CuO NPs to plants(40)

Wenli et al., (2020) they looked at how single walled carbon nanotubes (SwCNTs) affected the germination and development of soybean seedlings under drought stress. The outcomes showed that osmotic potential in PEG increased with an increase in germinability and germination percentage. Soybean seed germination was not improved by the carbon treatment, suggesting that SwCNTs structure may be crucial in this situation. The soybean seed coat's tough exterior may be penetrated by SwCNTs. SwCNTs may have a more accelerated and improved water absorption effect, which would account for their beneficial impact on soybean seed germination. Protection against oxidative stress during imbibition has also been suggested for peroxiredoxins contention of H2O2 in SwCNTs-treated seed was less than the control and activities of CAT, SOD, POD in SwCNTs-treated seeds were more than the control. alterations in the equilibrium of AOS content and the activities of detoxifying enzymes are also linked to alterations in soybean germination under drought stress(41).

Nayeri et al., (2023) investigated in depth the improvement of light quality and photosynthesis rate of chlorophyll a in the presence of Ag/ZnO different concentrations (0–50 mg/L) on wheat seedlings. wheat seeds with Ag/ZnO NPs at 15 mg/L for 12 h achieved an impressive germination rate of 99.33%.low Ag/ZnO NPs concentrations (up to 5mg/L) correlated with reduced shoot growth, higher concentrations exhibited a progressive increase, peaking at 15 mg/L. Root growth exhibited a parallel trend, showcasing the pivotal role of Zn ions in early coleoptile and radicle development. Nanoparticles can absorb and scatter the light with a wavelength of 394 nm and provide the extra light for the chlorophyll-a molecule(42)

Sun et al., 2021 studied the both drought-stressed and well-watered maize on effects of nano-ZnO (100 mg L^{-1}) in stomatal morphology, gas exchange, and major enzyme activities were examined. Study results revealed that under both drought stress and non-stress circumstances, plants treated with nano-ZnO exhibited greater Gsmax than N plants, showing that nano-ZnO improved maize's potential for productivity. due to nano-ZnO's ability to pass through endodermis via the symplastic pathway and enter xylem vessels, which may be in favour of maintaining higher Gsmax and, consequently, promoted photosynthetic carbon assimilation under drought. This may also be connected to a change in plant growth in nano-ZnO treated maize (43).

Semida et al., (2021) conducted the two field tests were undertaken in 2018 and 2019 to determine how three ZnO NP concentrations (0, 50, and 100 ppm) would affect eggplant growing under full irrigation (100 percent crop evapotranspiration; ETc) and drought stress (60% of ETc). Our findings showed that drought-stressed eggplants' growth-yield, water productivity (WP), and physiology-related indicators were all increased by exogenously applying ZnO NP. This growth-promotion in plants treated with ZnO NP is probably due to ZnO NP effects on hormonal signals that change root architecture for better plant adaptability to soil water deficiencies.In addition to controlling root development, ZnO NP also increases hormones like ABA and cytokinins that are associated to gene activity and expression and aid in the body's ability to withstand the effects of drought stress. ZnO NP foliar spraying may improve the recovery of the photosynthetic efficiency, providing more metabolites/photosynthesis for eggplant development(44).

El-Batal AI et al., (2023) studied the effects of wastewater irrigation of carrot plants treated with glycine betaine and proline alone or in combination with generated selenium nanoparticles (Se NPs) are being studied. The heavy metal-stressed carrot plants had higher soluble carbohydrates, soluble protein, and total proline than non-stressed plants. The amount of osmolytes and beta-carotene in the carrot crop is much lower in response to wastewater irrigation. When selenium nanoparticle treatment was combined with glycine betaine and proline, wastewater stressed carrot plants produced more osmolytes and beta-carotene than untreated plants, according to research on the interaction between wastewater irrigation and selenium nanoparticle treatment(45). The increased Soybean yield caused by the application of selenium nanoparticles may be attributed to the stimulatory effects of glycine betaine and proline, which scavenge ROS and promote the growth of stressed plants (46).

Conclusion:

Nanotechnology makes it feasible to achieve sustainable development goals by addressing important challenges like hunger, poverty, and assuring food safety by improving soil health and sustainable crop production. The present analysis looks at sustainable agricultural production strategies and how to deal with various soil stresses. The information provided here demonstrates the ability of NMs in soils to enhance microorganisms or agriculturally important microbes and support their activity to enhance the biodegradation of contaminants or lessen soil stresses.Degradation of the world's soil health is becoming a severe issue when it comes to supporting human needs, notably food security. The removal of contaminated soils is aided by the inclusion of NMs into biological processes. Nanotechnology has the potential to significantly modify agricultural practices, particularly when metal-based nanoparticles are applied. As the usage of these materials grows, it is essential to comprehend how they behave in the soil environment and how that may impact agricultural ecosystems. The ability of metal-based nanoparticles to aggregate or disperse in agricultural soil, with soil properties playing a crucial role in this process, has a significant impact on their mobility and bioavailability to plants and soil organisms. Their interaction with soil-dissolved organic matter is another crucial factor that may have an impact on the stability, reactivity, and absorption of metal-based nanoparticles by plants. Hetero aggregation with inorganic colloids, which changes the distribution and availability of these nanoparticles in the soil matrix, has an additional impact on the mobility and movement of these nanoparticles in agricultural soil. Dissolution, oxidation, and reduction processes alter the physicochemical properties of metal-based nanoparticles, which may affect how toxic they are to plants and soil organisms. Implementing this knowledge will be necessary for the ethical and effective use of metal-based nanoparticles in modern agricultural practices, which promotes both agricultural production and environmental preservation.

Future Perspectives in Nanotechnology in Agriculture:

1. We can ensure that metal-based nanoparticles are utilized ethically and successfully in modern agriculture by considering these possible results, developing a sustainable and cutting-edge farming system that boosts both productivity and sustainability.
2. There hasn't been a lot of study into how nanotechnology could affect or improve the composition and functionality of the rhizospheric microbiome since there aren't many studies that can be performed in a real-world setting.
3. Metal-based NPs may affect plants in both favourable and unfavourable ways. Because toxicity can manifest at any level, from the physiological to the biochemical and molecular, it is also possible for substances to have positive effects on growth, photosynthetic production, fruit yields, and pest management. The mechanisms of NPs phytotoxicity and the routes by which NPs move throughout plants are, however, still largely unclear.
4. Understanding how metal-based nanoparticles interact with naturally existing organic compounds or colloids in soil can be challenging due to their high reactivity.
5. Metal-based nanoparticle-based controlled release techniques can improve the fertilizer and pesticides' effective delivery.

Reference

1. Rajput VD, Kumari A, Upadhyay SK, Minkina T, Mandzhieva S, Ranjan A, et al. Can nanomaterials improve the soil microbiome and crop productivity? Agriculture. 2023;13(2):231.

2. Strer M, Svoboda N, Herrmann A. Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany. Environ Sci Eur. 2018;30:1–16.

3. Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, et al. Impact of climate change

on crops adaptation and strategies to tackle its outcome: A review. Plants. 2019;8(2):34.

4. Klaine SJ, Alvarez PJJ, Batley GE, Fernandes TF, Handy RD, Lyon DY, et al. Nanomaterials in the environment: behavior, fate, bioavailability, and effects. Environ Toxicol Chem An Int J. 2008;27(9):1825–51.
5. Chen H. Metal based nanoparticles in agricultural system: behavior, transport, and interaction with plants. Chem Speciat Bioavailab. 2018;30(1):123–34.
6. Deb SK, Shukla MK. A review of dissolved organic matter transport processes affecting soil and environmental quality. J Environ Anal Toxicol. 2011;1(02).
7. Dickson D, Liu G, Li C, Tachiev G, Cai Y. Dispersion and stability of bare hematite nanoparticles: effect of dispersion tools, nanoparticle concentration, humic acid and ionic strength. Sci Total Environ. 2012;419:170–7.
8. Praetorius A, Labille J, Scheringer M, Thill A, Hungerbühler K, Bottero J-Y. Heteroaggregation of titanium dioxide nanoparticles with model natural colloids under environmentally relevant conditions. Environ Sci Technol. 2014;48(18):10690–8.
9. Labille J, Harns C, Bottero J-Y, Brant J. Heteroaggregation of titanium dioxide nanoparticles with natural clay colloids. Environ Sci Technol. 2015;49(11):6608–16.
10. Feng Y, Liu X, Huynh KA, McCaffery JM, Mao L, Gao S, et al. Heteroaggregation of graphene oxide with nanometer-and micrometer-sized hematite colloids: Influence on nanohybrid aggregation and microparticle sedimentation. Environ Sci Technol. 2017;51(12):6821–8.
11. Ha N, Seo E, Kim S, Lee SJ. Adsorption of nanoparticles suspended in a drop on a leaf surface of Perilla frutescens and their infiltration through stomatal pathway. Sci Rep. 2021;11(1):11556.
12. Wohlmuth J, Tekielska D, Čechová J, Baránek M. Interaction of the nanoparticles and plants in selective growth stages—Usual effects and resulting impact on usage perspectives. Plants. 2022;11(18):2405.
13. Zhu J, Li J, Shen Y, Liu S, Zeng N, Zhan X, et al. Mechanism of zinc oxide nanoparticle entry into wheat seedling leaves. Environ Sci Nano. 2020;7(12):3901–13.

14. Pérez-de-Luque A. Interaction of nanomaterials with plants: what do we need for real applications in agriculture? Front Environ Sci. 2017;5:12.

15. Lv J, Zhang S, Luo L, Zhang J, Yang K, Christie P. Accumulation, speciation and uptake pathway of ZnO nanoparticles in maize. Environ Sci Nano. 2015;2(1):68–77.

16. Hubbard JD, Lui A, Landry MP. Multiscale and multidisciplinary approach to understanding nanoparticle transport in plants. Curr Opin Chem Eng. 2020;30:135–43.

17. Ma X, Yan J. Plant uptake and accumulation of engineered metallic nanoparticles from lab to field conditions. Curr Opin Environ Sci Heal. 2018;6:16–20.

18. Noori A, Ngo A, Gutierrez P, Theberge S, White JC. Silver nanoparticle detection and accumulation in tomato (Lycopersicon esculentum). J Nanoparticle Res. 2020;22:1–16.

19. Servin A, Elmer W, Mukherjee A, De la Torre-Roche R, Hamdi H, White JC, et al. A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanoparticle Res. 2015;17:1–21.

20. Saien J, Hasani R. Hydrodynamics and mass transfer characteristics of circulating single drops with effect of different size nanoparticles. Sep Purif Technol. 2017;175:298–304.

21. Peng C, Tong H, Shen C, Sun L, Yuan P, He M, et al. Bioavailability and translocation of metal oxide nanoparticles in the soil-rice plant system. Sci Total Environ. 2020;713:136662.

22. Maiti S, El Fahime E, Benaissa M, Kaur Brar S. Nano-ecotoxicology of natural and engineered nanoparticles for plants. In: Nanomaterials in the Environment. 2015. p. 469–85.

23. Lowry G V, Avellan A, Gilbertson LM. Opportunities and challenges for nanotechnology in the agri-tech revolution. Nat Nanotechnol. 2019;14(6):517–22.

24. Karuppanapandian T, Wang HW, Prabakaran N, Jeyalakshmi K, Kwon M, Manoharan K, et al. 2, 4-dichlorophenoxyacetic acid-induced leaf senescence in mung bean (Vigna radiata L. Wilczek) and senescence inhibition by co-treatment with silver nanoparticles. Plant Physiol Biochem. 2011;49(2):168–77.

25. Behboudi F, Tahmasebi Sarvestani Z, Kassaee MZ, Modares Sanavi SAM, Sorooshzadeh

A, Ahmadi SB. Evaluation of chitosan nanoparticles effects on yield and yield components of barley (Hordeum vulgare L.) under late season drought stress. J Water Environ Nanotechnol. 2018;3(1):22–39.

26. Hashem AH, Abdelaziz AM, Askar AA, Fouda HM, Khalil AMA, Abd-Elsalam KA, et al. Bacillus megaterium-mediated synthesis of selenium nanoparticles and their antifungal activity against Rhizoctonia solani in faba bean plants. J Fungi. 2021;7(3):195.

27. Elgindy N, Elkhodairy K, Molokhia A, ElZoghby A. Biopolymeric Nanoparticles for Oral Protein Delivery: Design and. Vitro; 2011.

28. Krishnappa S, Kalikeri S, Garampalli RKH, Kachintaya CK. A brief review of the impact of silver nanoparticles on agriculture and certain biological properties: A case study. Int J Heal Allied Sci. 2022;11(1):9.

29. Anandaraj K, Natarajan N. Effect of nanoparticles for seed quality enhancement in onion [Allium cepa (Linn) cv. CO (On)] 5. Int J Curr Microbiol App Sci. 2017;6:3714–24.

30. Cai L, Liu M, Liu Z, Yang H, Sun X, Chen J, et al. MgONPs can boost plant growth: evidence from increased seedling growth, morpho-physiological activities, and Mg uptake in tobacco (Nicotiana tabacum L.). Molecules. 2018;23(12):3375.

31. Avestan S, Ghasemnezhad M, Esfahani M, Byrt CS. Application of nano-silicon dioxide improves salt stress tolerance in strawberry plants. Agronomy. 2019;9(5):246.

32. Faraji J, Sepehri A. Ameliorative effects of TiO 2 nanoparticles and sodium nitroprusside on seed germination and seedling growth of wheat under PEG-stimulated drought stress. J Seed Sci. 2019;41:309–17.

33. Basahi M. Seed germination with titanium dioxide nanoparticles enhances water supply, reserve mobilization, oxidative stress and antioxidant enzyme activities in pea. Saudi J Biol Sci. 2021;28(11):6500–7.

34. Larue C, Baratange C, Vantelon D, Khodja H, Surblé S, Elger A, et al. Influence of soil type on TiO2 nanoparticle fate in an agro-ecosystem. Sci Total Environ. 2018;630:609–17.

35. Mustafa H, Ilyas N, Akhtar N, Raja NI, Zainab T, Shah T, et al. Biosynthesis and

characterization of titanium dioxide nanoparticles and its effects along with calcium phosphate on physicochemical attributes of wheat under drought stress. Ecotoxicol Environ Saf. 2021;223:112519.

36. Jaberzadeh A, Moaveni P, MOGHADAM HRT, Zahedi H. Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. Not Bot horti Agrobot cluj-napoca. 2013;41(1):201–7.

37. Jalali M, Ghanati F, Modarres-Sanavi AM. Effect of $Fe3O4$ nanoparticles and iron chelate on the antioxidant capacity and nutritional value of soil-cultivated maize (Zea mays) plants. Crop Pasture Sci. 2016;67(6):621–8.

38. Shankramma K, Yallappa S, Shivanna MB, Manjanna J. Fe 2 O 3 magnetic nanoparticles to enhance S. lycopersicum (tomato) plant growth and their biomineralization. Appl Nanosci. 2016;6:983–90.

39. Yang Z, Xiao Y, Jiao T, Zhang Y, Chen J, Gao Y. Effects of copper oxide nanoparticles on the growth of rice (Oryza sativa L.) seedlings and the relevant physiological responses. Int J Environ Res Public Health. 2020;17(4):1260.

40. Wang Z, Von Dem Bussche A, Kabadi PK, Kane AB, Hurt RH. Biological and environmental transformations of copper-based nanomaterials. ACS Nano. 2013;7(10):8715–27.

41. Wenli S, Shahrajabian MH, Huang Q. Soybean seeds treated with single walled carbon nanotubes (SwCNTs) showed enhanced drought tolerance during germination. Int J Adv Biol Biomed Res. 2020;8:9–16.

42. Nayeri S, Dolatyari M, Mouladoost N, Nayeri S, Zarghami A, Mirtagioglu H, et al. Ag/ZnO core–shell NPs boost photosynthesis and growth rate in wheat seedlings under simulated full sun spectrum. Sci Rep. 2023;13(1):14385.

43. Sun L, Song F, Zhu X, Liu S, Liu F, Wang Y, et al. Nano-ZnO alleviates drought stress via modulating the plant water use and carbohydrate metabolism in maize. Arch Agron Soil Sci. 2021;67(2):245–59.

44. Semida WM, Abdelkhalik A, Mohamed GF, Abd El-Mageed TA, Abd El-Mageed SA, Rady MM, et al. Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (Solanum melongena L.). Plants. 2021;10(2):421.

45. El-Batal AI, Ismail MA, Amin MA, El-Sayyad GS, Osman MS. Selenium nanoparticles induce growth and physiological tolerance of wastewater-stressed carrot plants. Biologia (Bratisl). 2023;1–17.

46. Zeeshan M, Hu YX, Guo XH, Sun CY, Salam A, Ahmad S, et al. Physiological and transcriptomic study reveal SeNPs-mediated AsIII stress detoxification mechanisms involved modulation of antioxidants, metal transporters, and transcription factors in Glycine max L.(Merr.) roots. Environ Pollut. 2023;317:120637.