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Bioanalytical Perspectives on the Role of Nanoparticles in Enhancing Plant Stress Tolerance and Yield Quality.

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Abstract

Generally, abiotic stresses have adverse impacts on plant growth and development, which affects agricultural productivity, causing food security problems, and resulting in economic losses. To reduce the negative effects of environmental stress on crop plants, novel technologies, such as nanotechnology, have emerged. Implementing nanotechnology in modern agriculture can also help improve the efficiency of water usage, prevent plant diseases, ensure food security, reduce environmental pollution, and enhance sustainability in agriculture. In this regard, nanoparticles can help combat nutrient deficiencies, promote stress tolerance, and improve the yield and quality of crops. Nanoparticles eliminate nutrient deficiencies in plants, increase the tolerance of plants to stress conditions by enabling the enzyme activities and the adhesion of bacteria that promote plant growth to the roots under abiotic stress conditions. In this review, the role of nanoparticles in ameliorating adverse effects on plants exposed to abiotic stress conditions will be emphasized. NPs exhibit alleviating effects against drought stress via induction of

physiological and biochemical readjustments accompanied by modulation of gene expression involved in drought response/tolerance. NPs ameliorate drought-induced reduction in carbon assimilation via increasing the photosynthetic activity. The improved root growth, upregulation of aquaporins, modification of intracellular water metabolism, accumulation of compatible solutes, and ion homeostasis are the major mechanisms used by NPs to mitigate the osmotic stress caused by water deficit. NPs reduce water loss from leaves through stomatal closure due to fostered abscisic acid (ABA) accumulation and ameliorate oxidative stress damage by reducing reactive oxygen species and activating the antioxidant defense system.

Key Words: Global warming, food crisis, nanotechnology, poverty, water crisis, water deficit, drought stress, abscisic acid (ABA)

1. Introductions

In the current global scenario, food production and distribution remain under severe strain because of the rising population, climate change, environmental contamination, and increased water and energy demands (Adrees et al. 2020; Usman et al. 2020; Van Nguyen et al. 2022). To add to this, current agricultural practices consume a large volume of resources. For example, although the annual crop production in the USA exceeds three billion tonnes, it requires 187 million tonnes of fertilizers, 4 million tonnes of pesticides, 2.7 trillion cubic meters of water (roughly 70% of all global freshwater), and over two quadrillion British thermal units (BTU) of energy (Kah and Hofman 2014).

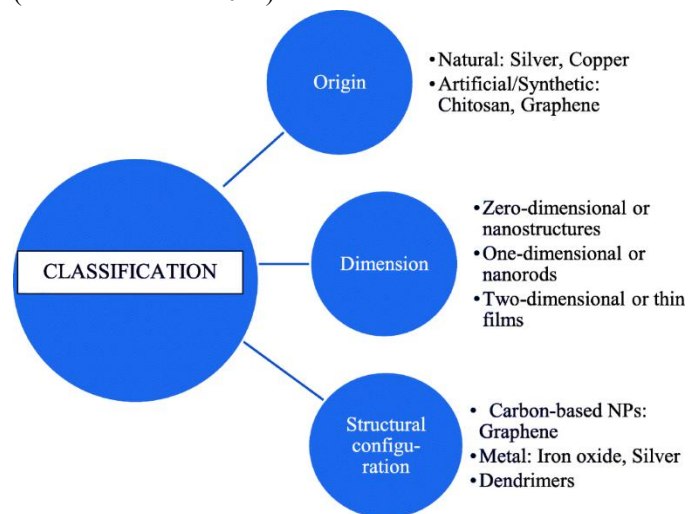


Figure 1: classification of Nanoparticles on the basis of Origin, dimension and Structure.

According to the FAO (2017), the world's population is expected to reach 10 billion by 2050, resulting in a 50% increase in food demand, particularly in developing nations. In developing countries, notably India, agriculture is one of the most essential components of the national economy. Increasing

food production rates contribute significantly to the growth of the nation’s GDP. In addition, more than 60% of the population relies on it for sustenance, fodder, fuel, and fiber. The decline

in food grain productivity can lead to food scarcity and a decline in nutrition security. Limitations in water and agricultural

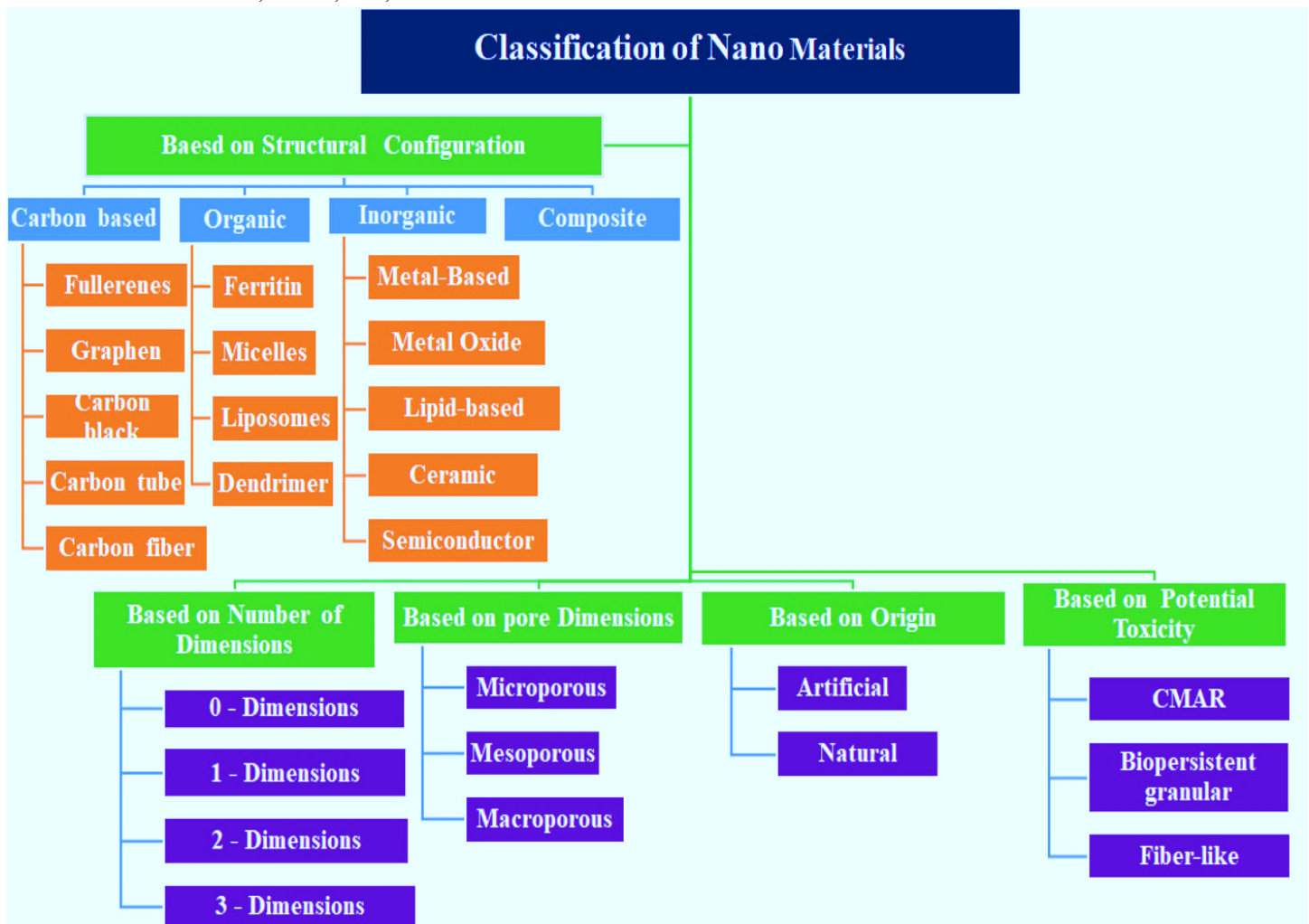


Figure 2: Classification of nanoparticles based on structure, dimension, Origin and Potential Toxicity.

land availability is attributed as a major reason for declining food productivity trends, while the deterioration of water, soil nutrients, climate change, and so on can accentuate this problem (Bisht et al. 2022; Van Nguyen et al. 2022). Nanotechnology could be a potential tool in remodeling various aspects of agriculture, from soil remediation to food packaging (Alabdallah et al. 2021). NPs can play various roles in agriculture and can be widely used as fertilizers, pesticides, herbicides, insecticides, growth regulators, nanocarriers, Nano sensors, and Nano barcodes. Furthermore, nanotechnology can be applied in water filtration and soil remediation (Prasad et al. 2017; Al-Khayri et al. 2023). NPs can serve as cargo, and they can deliver genetic material and protein, resulting in genetic modification of medicinal and aromatic plants with higher resistance to stresses, as well as contributing to higher yield and enhanced nutrient uptake (Siddiqui et al. 2015; Al-Khayri et al. 2023). Furthermore, nanoscale materials can be used to monitor crop yield using geospatial techniques and

Nano sensors (Usman et al. 2020; Sharma et al. 2021). Nano barcodes can tag proteins associated with pathogenicity, which can be used for rapid diagnostics and control of pathogen infections in crops (Hayat et al. 2023), making them key players in precision agriculture. Sessile organisms such as plants are constantly exposed to an array of abiotic elements. Environmental variations such as drought, salinity, alkalinity, flooding, and mineral toxicity/deficiencies can cause stress to crops resulting in substantial yield reduction. Although some plants have the innate ability to withstand stresses, this is not the case with many plants (Hayat et al. 2023; Luz et al. 2023). Water is necessary for the plant life cycle as it is involved in nutrient transport. Stress caused by water deficit conditions due to physical lack of water, i.e., drought and physiological water inaccessibility, is most common in arid and semiarid regions (Luz et al. 2023). Drought stress impairs the photosynthesis, nutrient uptake, osmotic and antioxidant processes, and overproduction of reactive oxygen species (ROS) in drought-

stressed plants, leading to the denaturation of proteins, DNA damage, and lipid peroxidation, which hinders cell growth and elongation, resulting in poor plant growth and productivity (Waqas Mazhar et al. 2022; Hayat et al. 2023). Recent studies have highlighted the role of metal-based and carbon-based NPs in mitigating drought stress by inducing tolerance (Linh et al. 2020; Shekhawat et al. 2021).

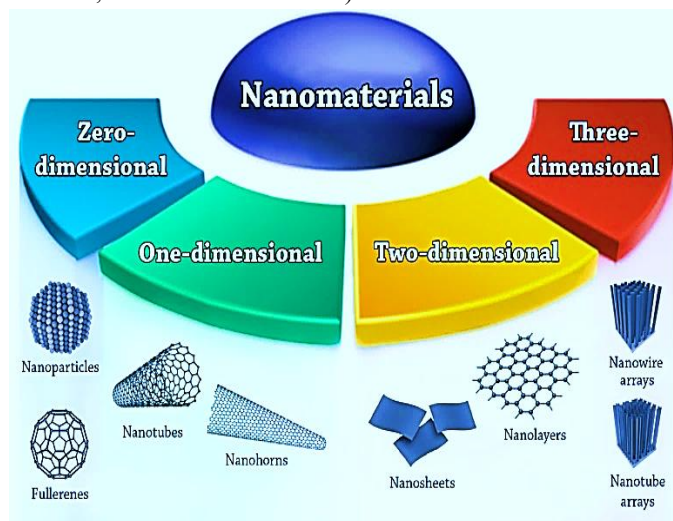


Figure 3: Classification of Nano Particles on the basis of Dimension

Photorespiration can lead Carbon-based NMs such as graphene, fullerene, fullerol, and carbon NTs, and metal-based NPs, such as ZnO, TiO₂, Fe, and Cu NPs, have been widely used to ameliorate drought stress by increasing water and nutrient uptake via stress tolerance and upregulation of genes involved in cell growth (Linh et al. 2020; Shekhawat et al. 2021). NPs have been reported to enhance germination parameters, growth rate, biomass, and yield, regulate. The positive effects of carbon and metal-based NPs depend on their concentration, morphology, surface properties, mode of application, and type of plant species. In this review, we have compiled the current studies on NP-mediated drought mitigation and tolerance mechanisms to improve plant yield characteristics. Moreover, we have also highlighted the role of inorganic and organic nanoparticles in developing resilient crops for sustainable productivity.

2. CLASSIFICATION OF NANOPARTICLES

Nanoparticles (NPs) are mainly classified into various classes based on their morphology, size, and physical & chemical properties. They are mainly classified into organic, inorganic, and carbon-based NPs.

A. Organic Nanoparticles

Organic nanoparticles are small particles made of aggregated molecules or polymers. These materials are of broad interest owing to ease of fabrication and wide range of aggregated structures that can be achieved. The morphology of the aggregated molecules/polymers are not easily accessible in

annealed thin films, providing a useful platform for fundamental photophysical studies. They are also of interest for applications in photovoltaics, where their small size shortens the distance changes need to travel in order to be extracted.

They are typically synthesized using one of two methods: Mini emulsion and reprecipitation. In the miniemulsion method, an aqueous solution containing surfactant and an organic solvent containing the molecule or polymer units are stirred together to make a microemulsion with large droplets of oil in water. Sonification of this macroemulsion forms a miniemulsion and subsequent purification steps remove excess surfactant to leave a concentrated aqueous dispersion.

Organic nanoparticles are the solid particles composed of organic compounds such as lipids or polymers with a diameter in the range of 10 nm to 1 μm (Ealia S. A. M. & Saravanakumar M. P, 2019; Khalisanni K. et al., 2020; Khan I., Khalid S., & Khan I., 2019). Some commonly known organic NPs are dendrimers, liposomes, micelles, ferritin etc. These organic NPs are environment friendly, biodegradable, non-toxic, economical and more suitable in biomedical field. Both micelles and liposomes have a hollow core also known as nano capsules and are sensitive to thermal and electromagnetic radiations. These unique properties make organic NPs an ideal choice for drug delivery. They are highly efficient in target drug delivery.

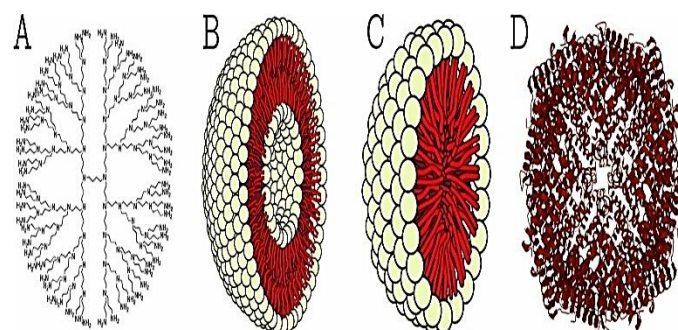


Figure 4: Types of organic NPs. A Dendrimers; B liposomes; C micelles; and D ferritin, Sources: Nadeem Joudeh et al, 2022.

B. Inorganic Nanoparticles Inorganic nanoparticles are the particles that are not made of carbon. It includes metal and metal oxides (Ealia S. A. M. & Saravana Kumar M. P, 2019; Khalisanni K. et al., 2020; Khan I., Khalid S., & Khan I., 2019). As compared with organic NPs in inorganic NPs enormous research and commercial investments has been made in inorganic NPs.

1) Metal Based Nanoparticles

Metal based nanoparticles can be obtained from metals such as aluminum (Al), gold (Au), silver (Ag), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), lead (Pb) and zinc (Zn). The most widely used metals in are Ag, Au, Cu, Fe and Zn. Transition

metals are found to be the best candidates for the synthesis of metal-based NPs due to the presence of partially filled d-orbitals which make them more redox active (Elena S. L., et al., 2020).

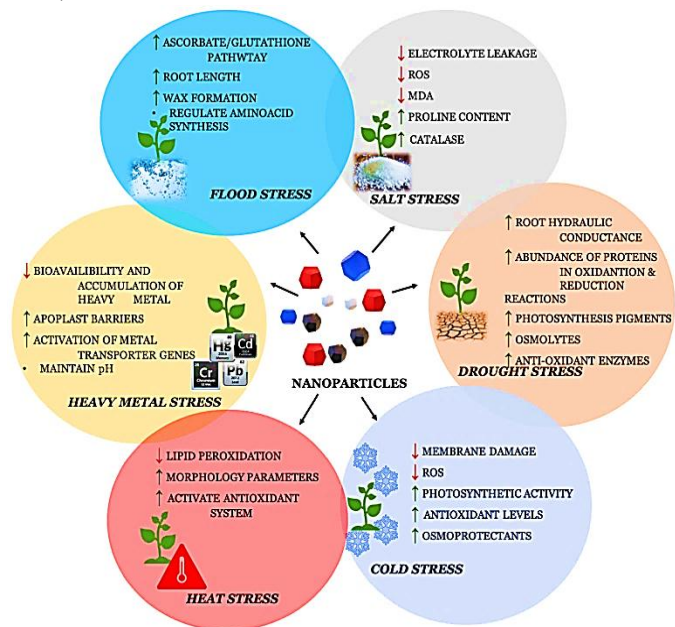


Figure 5: Effect of Nanoparticles on Biotic and Abiotic Stress

This in turn facilitates nanoparticle aggregation. Metal based NPs have size in the range of 10 to 100 nm. They exist in different shapes such as spherical and cylindrical. They show unusual properties such as high surface area to volume ratio, pore size, surface charge and surface charge density, crystalline and amorphous structures, high reactivity, and sensitivity to environmental factors such as air, moisture, heat, sunlight etc. Due to these unusual properties, they find promising applications in numerous research areas.

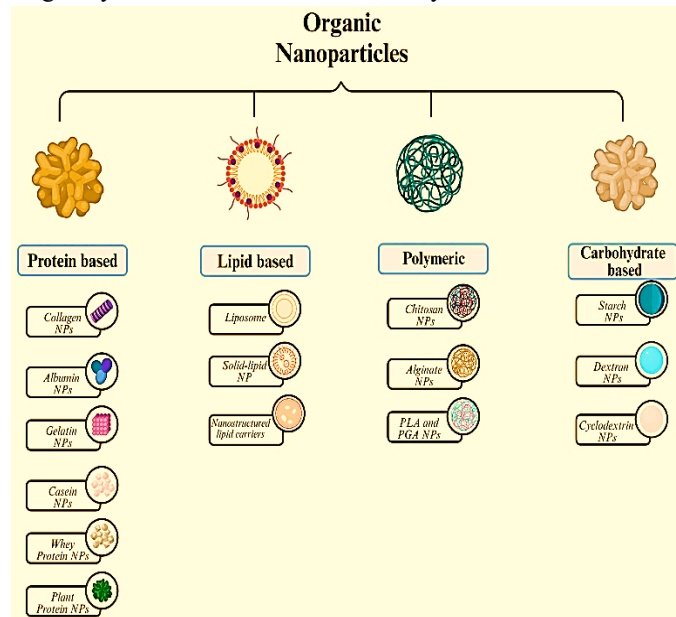
2) Metal Oxide-Based Nanoparticles Metal based NPs can be converted into their corresponding oxides known as metal oxides-based NPs. Metal oxides-based NPs have exceptional properties as compared with their metal counterparts. Some examples of metal oxides-based NPs are Iron oxide (Fe₂O₃), Magnetite (Fe₃O₄), Aluminum oxide (Al₂O₃), Cerium oxide (CeO₂), Silicon dioxide (SiO₂), Titanium oxide (TiO₂), Zinc oxide (ZnO) (Sathyanarayanan, M. B., Bala Chandranath, R., Genji Srinivasulu, Y., Kannaiyan, S. K., & Subbiah doss, G., 2013). These metal oxides-based NPs found to be more reactive and efficient.

C. Carbon Based Nanoparticles The nanoparticles composed of carbon are known as carbon-based NPs. Carbon based NPs can exist in different shapes such as tube- shaped, horn- shaped, spherical, or ellipsoidal. Two major classes of carbon-based NPs are fullerene and carbon nanotubes (CNTs). Other classes of carbon- based NPs are graphene, nanofibers, and carbon black (Bhaviripudi S., Mile E., Iii S. A. S., Zare A. T.,

Dresselhaus M. S., Belcher A. M. & Kong J., 2007; Patel K. P., Singh R. K., Kim, H. W., 2019).

1) Fullerene

Nobel laureates H. W. Kroto, R. F. Curl and R. E. Smalley discovered fullerenes in the year 1985. The fullerene family includes a number of atomic clusters (C_n) where n > 20. Fullerene C₆₀ is the most common fullerene, having 60 carbon atoms. It is also known as a buck ball. It is spherical in shape. Each carbon atom is sp² hybridized and are linked together by covalent bonds. All the carbon atoms located at the vertices of 20 hexagons and 12 pentagons. About 28 to 1500 carbon atoms form the spherical structure with diameters up to 8.2 nm for a single layer and 4 to 36 nm for multi-layered fullerenes.



2) Carbon

Nanotubes (CNTs) Carbon nanotubes are allotropes of carbon and were discovered by the Japanese scientist S. Iijima in the year 1991. CNTs are having exceptional properties such as rigidity, strength and elasticity which have created noteworthy commercial interests. They also show high thermal and electrical conductivity. CNTs are cylindrical structures with a diameter of several nanometers, consisting of rolled graphene sheets. They may vary in length, diameter, symmetry and number of layers. The ends of CNTs can either be hollow or closed by a half fullerene molecule. Depending on their structure, they can be broadly classified into two main groups: (a) single-walled carbon nanotubes (SWCNTs) having a diameter of 1-3 nm and a few micrometers in length and (b) multi-walled carbon nanotubes (MWCNTs) with a diameter of 5-40 nm and a length of around 10 μm. However, CNTs with a length of 550 nm have also been reported.

3) Graphene

Graphene is another allotropic form of carbon. It has a two-dimensional honeycomb-like lattice. A graphene sheet is generally 1 nm in thickness.

4) Carbon Nanofibers

Carbon nanofibers (CNFs) are also made up of graphene sheets. In this, graphene layers are arranged as stacked cones, cups, or plates. CNFs have excellent mechanical properties and high thermal and electrical conductivity. Their diameter varies from 10 nm to 500 nm. Hence, these CNFs find application in many fields such as drug delivery, energy devices, sensors, nanocomposites, photocatalysis, etc.

5) Carbon Black

Carbon black nanoparticles (CBNP), or Nano powders, are amorphous materials mainly composed of elemental carbon. It is also known as 'soot' or 'shouen.' These are spherical in shape with diameters in the range of 20 to 70 nm. CBNP form agglomerates of 500 nm size due to high interaction between the particles. These generally find application in laser printing and copy machine inks. They are also used as rubber reinforcement preservatives as well as pigments in plastic industries.

3. SYNTHESIS OF NANOPARTICLES

Various methods have been employed to synthesize nanoparticles (NPs) with controlled shape, size, dimensions, and structure. There are two mains

A Comprehensive Review of Nanoparticles: From Classification to Application and Toxicity

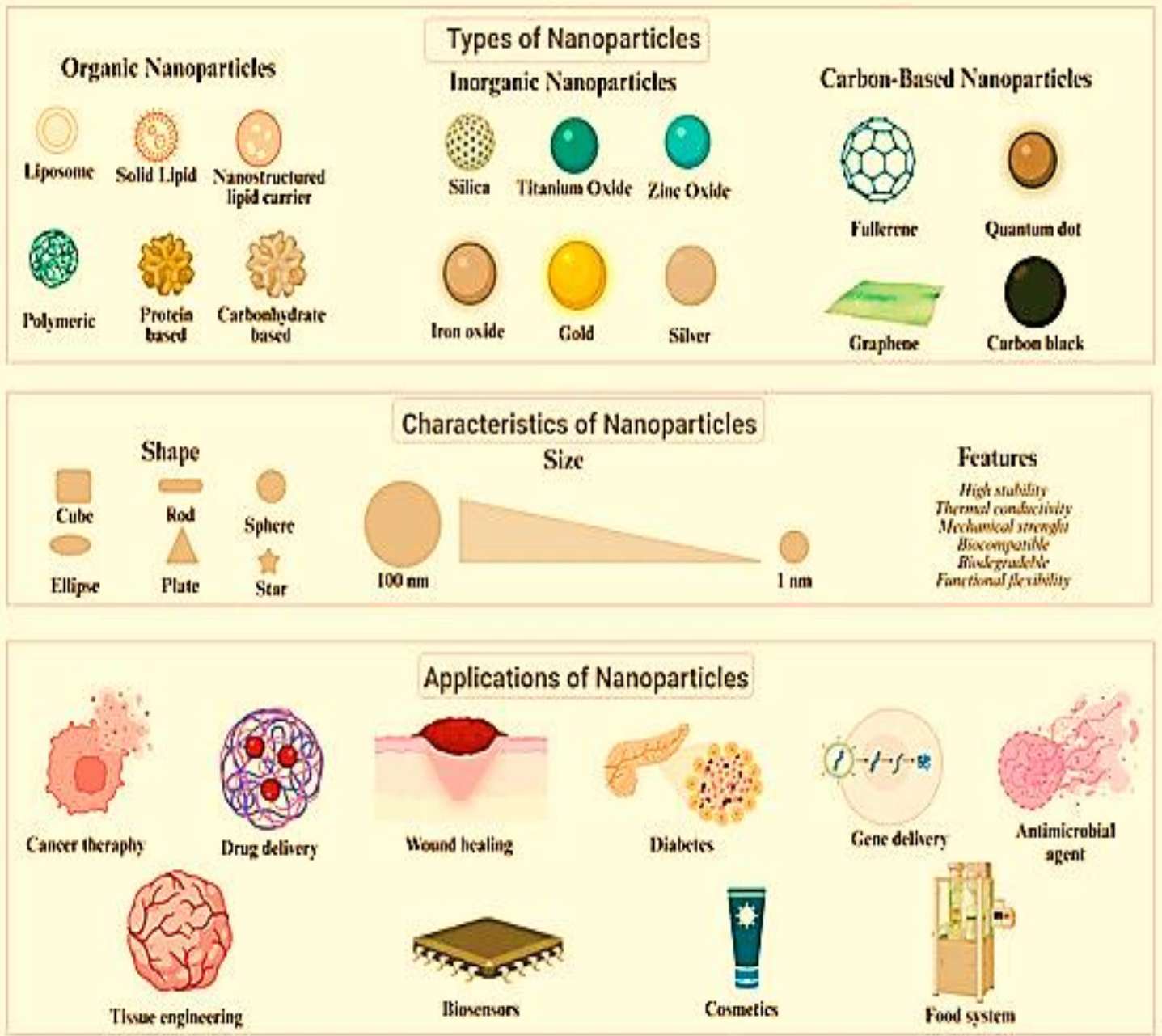


Figure 5: Representative scheme of NPs.

approaches for the synthesis of NPs viz., Top- down and Bottom- up approach (Arole, V. M., & Munde, S. V., 2014; Hasan, S., 2015; Khan, F. A., 2020; Khan I., Khalid S., & Khan I., 2019; Rane, A. V., Kanny, K., Abitha, V. K., & Thomas, S., 2018;).These methods are further divided into different categories based on the operations and reaction conditions (Scheme 1 & 2).

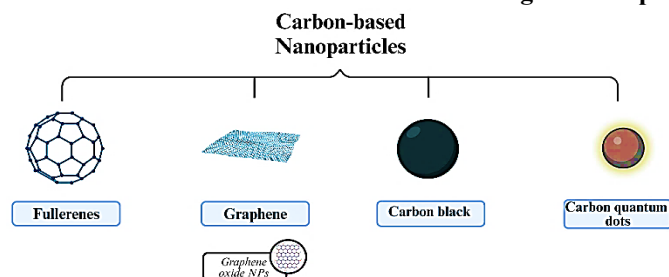


Figure 5.1: Carbon-Based Nanoparticles

A. Top-Down Approach The top-down approach involves the breaking down of the bulk material into nanosized particles. It is a destructive method. Top down approaches are simpler and depend either on the removal or division of bulk material or the miniaturization of bulk fabrication processes to produce desired structure with appropriate properties. Mechanical milling, nanolithography, laser ablation, sputtering, and thermal decomposition are some of the most widely used nanoparticle synthesis methods.

B. Bottom-Up Approach The bottom-up or constructive method is an alternative approach which employs build-up approach where nanoparticles are built up from clusters, which in turn are obtained from atoms. Scheme

This approach generally involves sedimentation and reduction techniques. This approach is considered to be more economical, as it has the potential of creating less waste. The most commonly used examples of this method are Sol-gel, spinning, green synthesis, chemical vapor deposition (CVD), pyrolysis and biosynthesis.

4. APPLICATIONS OF NANOPARTICLES

Nanoparticles exhibit unique physical and chemical properties such as electronic & optical properties, mechanical properties, magnetic properties & thermal properties. This uniqueness has led to its application in different areas. Some of the significant applications of NPs are discussed below: A. Medicine Nanoparticles have made major contributions to clinical medicine in the areas of medical imaging and drug/gene delivery. Iron oxide particles such as magnetite (Fe_3O_4) or its oxidized form, hematite (Fe_2O_3), are most commonly employed for biomedical applications. Ag NPs are being used increasingly in wound dressings, catheters, and various households' products due to their antimicrobial activity. Gold nanoparticles are emerging as promising agents for cancer therapy, as drug carriers, photothermal agents, contrast agents and radiosensitizers (Cai, W., Gao, T., Hong, H., & Sun, J., 2008; Jain, S., Hirst, D. G., & O'Sullivan, J., 2012; Sztandera, K., Gorzkiewicz, M., & Klajnert-Maculewicz, B., 2018). Over past few decades there has been considerable interest in developing biodegradable NPs as effective drug delivery

devices. Various polymers have been used in drug delivery research as they can effectively deliver the drugs to the target site thus increases the therapeutic benefit, while minimizing side effects. B. Environmental Remediation Nanoparticles are commonly used for environmental remediation, since they are highly flexible towards both in situ and ex situ applications in aqueous systems. Silver nanoparticles (AgNPs) due to their antibacterial, antifungal, and antiviral activity has been extensively used as water disinfectants (Zhang, C., Hu, TiO₂ NPs have been increasingly studied for waste treatment, air purification (Haider, A., Al-Anbari, R., Kadhim, G., & Jameel, Z., 2018), self-cleaning of surfaces (Veziroglu, S., Hwang, J., Drewes, J., Barg, I., Shondo, J., Strunskus, T., & Aktas, O. C., 2020), and as a photocatalyst in water treatment (Peng, Y., Yu, Z., Pan, Y., & Zeng, G., 2018) application due to their characterized low-cost, non-toxicity, semiconducting, photocatalytic, electronic, gas sensing, and energy converting properties. Z., Li, P., & Gajaraj, S., 2016).

C. Mechanical Industries

Owing to excellent young modulus, stress, and strain properties, NPs finds applications in mechanical industries especially in coating, lubricants (Ghaednia, H., Hossain, M. S., & Jackson, R. L., 2016), adhesives (Cao, Z., & Dobrynin, A. V., 2016) and manufacturing of mechanically stronger nanodevices. Pal et al. (2021) reported two-step dip-coating method using silver nanoparticles (AgNPs) and the fluorine-free silane monomer, 3-(Trimethoxy silyl) propyl methacrylate (TMSPM) for the fabrication of hydrophobic coating on cotton fabric. D. Food Nanoparticles have been increasingly incorporated into food packaging to control the ambient atmosphere around food, keeping it fresh and safe from microbial contamination (Bhardwaj M. & Saxena D.C., 2017). Now-a-days, inorganic & metal NPs are extensively used as alternatives to petroleum plastics in the food packaging industry as they can directly introduce the anti-microbial substances on the coated film surface (Hosein Nejad, M., Jafari, S. M., & Katouzian, I., 2018).

Classification of Nanoparticles

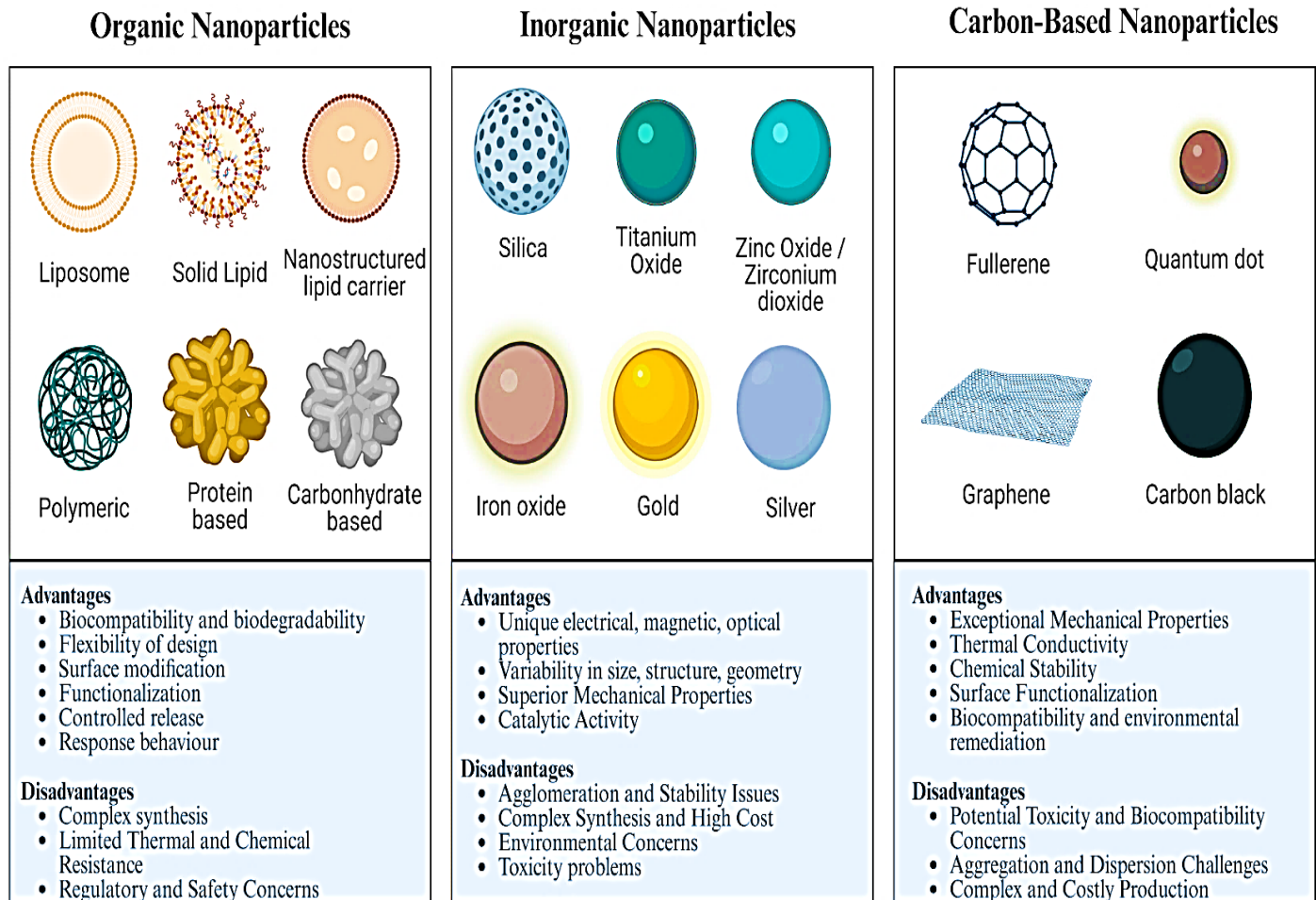


Figure 7: Sketch of Nanoparticle Classifications

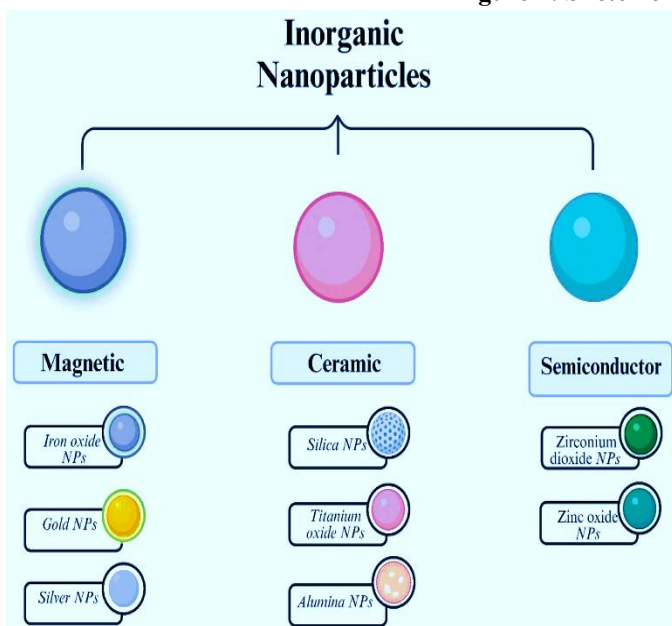


Figure 8: Classification of Inorganic Nano particles

E. Electronics Unique structural, optical and electrical properties of one-dimensional semiconductor and metals make them the key structural block for a new generation of electronic, sensors and photonic materials.

F. Energy Harvesting

Due to the scarcity of fossil fuels scientist have been shifting their research interests in the development of different strategies which can help in generating renewable energies from easily available resources at cheap cost. NPs are the suitable candidate for this purpose due to their large surface area, optical behavior and catalytic nature. NPs are widely used to generate energy from photoelectrochemical (PEC) and electrochemical water splitting (Avasare et al., 2015). Other advanced options such as electrochemical CO2 reduction to fuels precursors, solar cells and piezoelectric generators also utilized to generate energy. Ibrahim et al. (2019) reported use

of graphene as a source of energy as well as next generation smart energy storage devices.

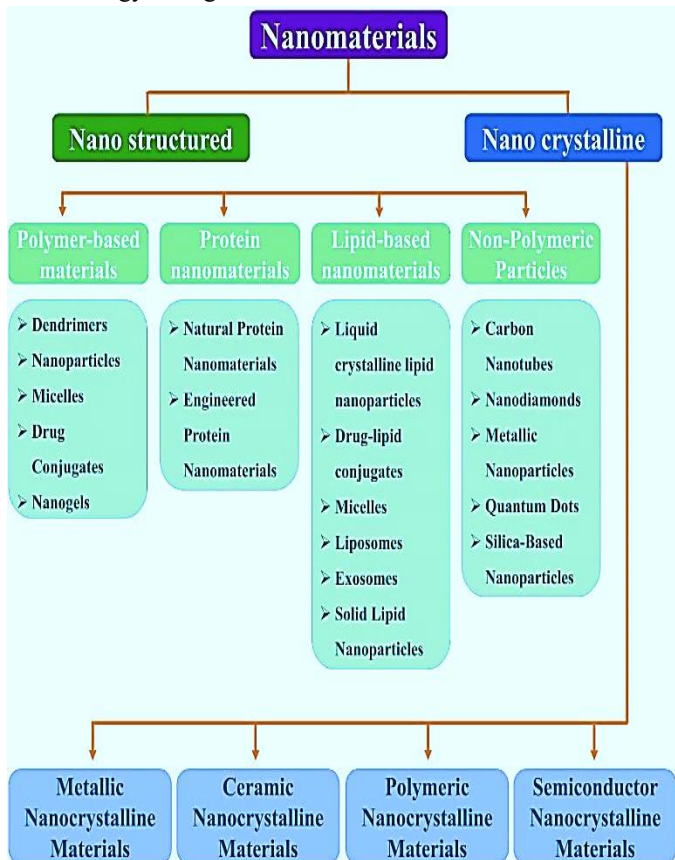


Figure 9: Sketch out the classification of nanomaterials.

Abiotic stress in plants is one of the main obstacles to global agricultural production and food security. Therefore, there is a need for the development of novel approaches to overcome these problems and achieve sustainability. Nanotechnology has emerged as one such novel approach to improve crop production through the utilization of nanoscale products, such as Nano fertilizer, Nano fungicides, Nano herbicides and Nano pesticides. Their ability to cross cellular barriers makes nanoparticles suitable for their application in agriculture. Since they are easily soluble, smaller, and effective for uptake by plants, nanoparticles are widely used as a modern agricultural tool. The implementation of nanoparticles has been found to be effective in improving the qualitative and quantitative aspects of crop production under various biotic and abiotic stress conditions.

5. Nanoparticles in Plants Abiotic Stress Management:

I. Climate changes abiotic stress nanoparticles molecular changes:

1. Nanoparticles in Salt-Stress Tolerance

Global-warming-driven water scarcity also forces irrigation with saline water in agricultural lands all over the world, which leads to enhanced salt content in the soil. Salinity (the buildup of excessive salt in the soil) is one of the main challenges to

modern agriculture, and it eventually stunts and impairs plant growth and development, ending in plant mortality (Isayenkov, S.V.; Maathuis, F.J.M.,2019; Mahmood, R.; Ijaz, M.; Qamar, S.; Bukhari, S.A.; Malik, K.,219).

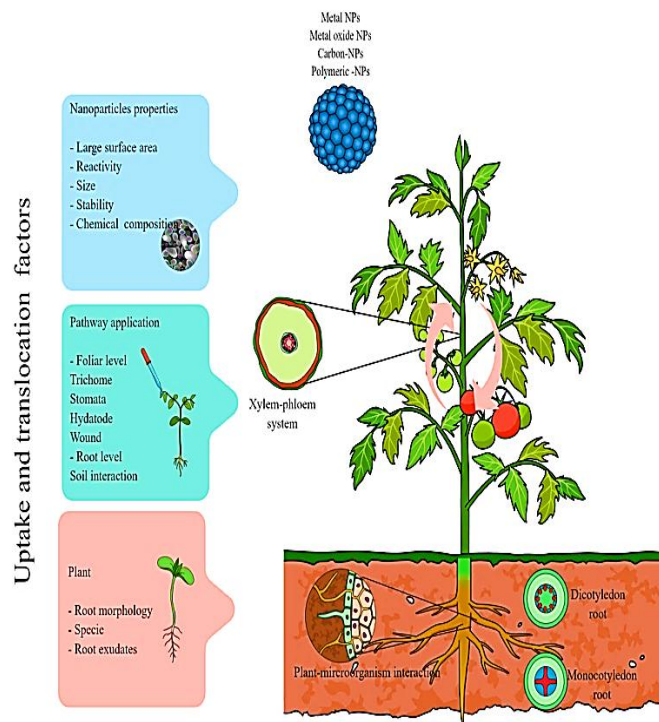


Figure 11: Representation scheme of the main routes used by nanoparticles for translocation in plants.

Most plants die when the NaCl content is higher than 200 mM. Salinity has a significant impact on every stage of the plant's life cycle, including seed germination, seedling development, vegetative growth, and blooming (Mohamed, H.I.; Sajjan, T.K.; Shaalan, R.; Bejjani, R.; Sassine, Y.N.; Basit, A. ,2022). Numerous horticultural crops, such as fruits, vegetables, and spices, are impacted by salinity. In addition to causing osmotic stress, water stress, oxidative stress, nutritional stress and reduced cell division, salt stress imbalances ionic strength, which has an impact on a number of biochemical, physiological and metabolic processes (Dong, F.; Yang, F.; Liu, Y.; Jia, W.; He, X.; Chai, J.; Zhao, H.; Lv, M.; Zhao, L.; Zhou, S.,2021; Sinha, R.K.; Verma, S.S.,2021). The response to various abiotic stress has been illustrated in Figures. According to Zulfiqar and Ashraf (Zulfiqar, F.; Ashraf, M. ,2021), the application of nanoparticles, such as Zn NPs, Ag NPs, SiO₂ NPs, Cu NPs, Fe NPs, Mn NPs, C NPs, Ti NPs, Ce NPs and K NPs, was effective in mitigating the toxic effects of salt stress in various plants. El-Sharkawy et al.,2017 found that the foliar application of K NPs in salt-sensitive *Medicago sativa* improved salt tolerance by reducing electrolyte leakage and enhancing the proline and antioxidant-enzyme content, such as that of catalase. Similarly, reduced oxidative stress was evident in the lower MDA and ROS levels and higher antioxidant activity in AgNPs-treated

pearl millet plants, which may have been caused by a decrease in Na^+ absorption in the leaves(Khan, I.; Raza, M.A.; Awan, S.A.; Shah, G.A.; Rizwan, M.; Ali, B.; Tariq, R.; Hassan, M.J.; Alyemeni, M.N.; Brestic, M.; et al.,2020). Increasingly

prevalent data suggest that applying nanoparticles to plants can considerably reduce the detrimental impacts of salt stress, and thus also control plant adaptations.

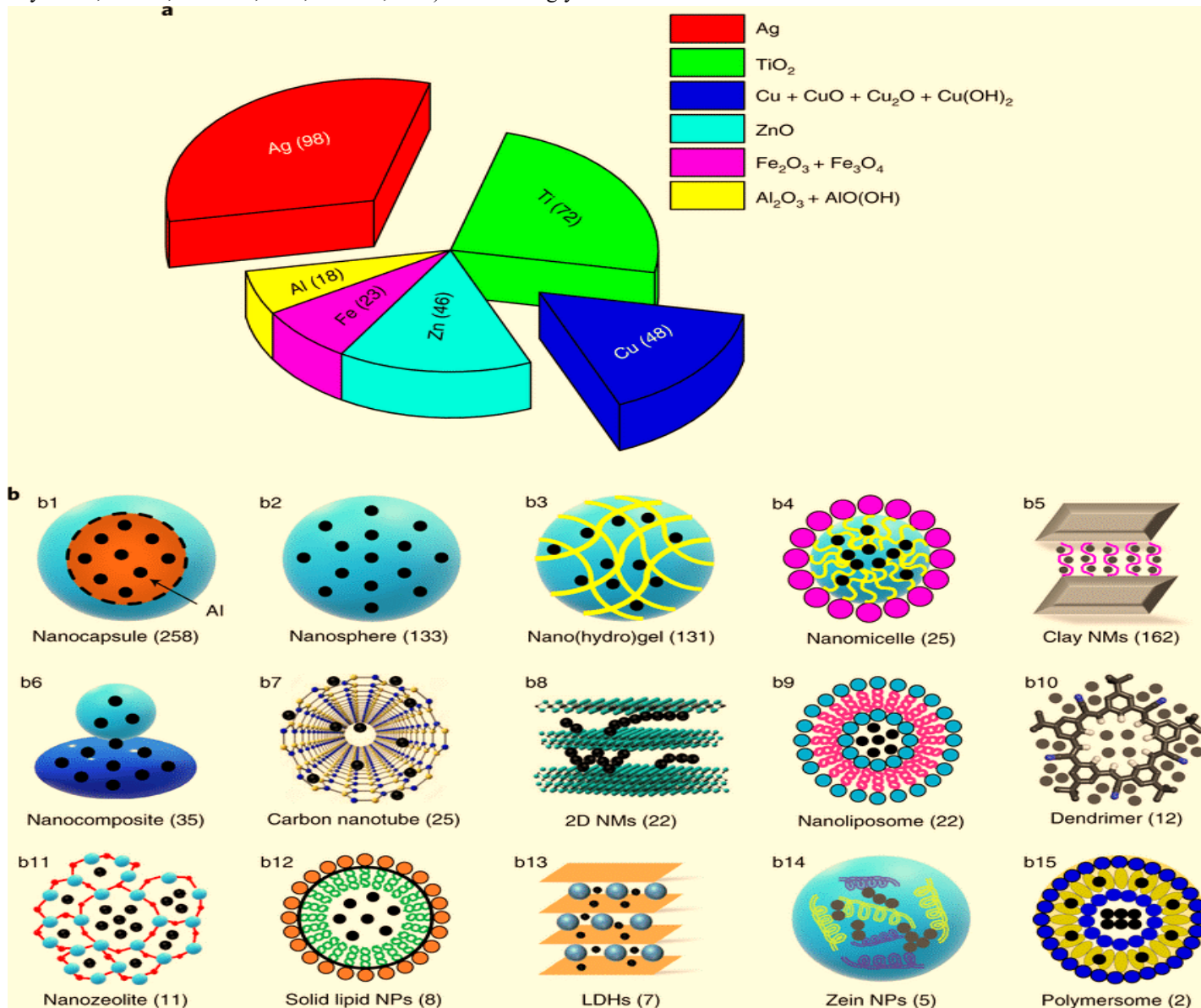


Figure 10: Classification of Nano pesticides were classified by analysis of 36,658 patents (among which 1,163 are Nano pesticides of interest; see Methods section). **a**, In Type 1 Nano pesticides, NMs are used directly as AIs. Metal-based NMs are the most widely applied Type 1 Nano pesticides and they include Ag-based NMs (as Nano bactericides, nonfungicides and Nano insecticides), Ti-based NMs (as Nano bactericides and Nano fungicides), Cu-based NMs (as Nano fungicides and Nano bactericides) and Zn-, Fe- and Al-based NMs. **b**, In Type 2 Nano pesticides, NMs serve as nanocarriers to encapsulate AIs to achieve controlled, targeted and synchronized release of AIs at the right target, time and dose (that is, through the RNDP). The AIs in Type 2 Nano pesticides are mainly conventional pesticides, such as atrazine, avermectin and glyphosate. The common nanocarrier types include polymers (b1–b4) such as chitosan, cellulose and polyethylene existing in the forms of Nano capsules (b1), nanospheres (b2), nano(hydro)gels (b3) and Nano micelles (b4), clay NMs (for example, silica, montmorillonite and kaolinite; b5), nanocomposites (b6), carbon nanotubes (CNTs; b7), 2D NMs (for example, graphene; b8), nanoliposomes (b9), dendrimers (b10), Nano zeolites (b11), solid lipid NPs (b12), layered double hydroxides (LDHs; b13), zein NPs (b14) and polymerases (b15). The numbers in parentheses indicate the number of patents indexed by Google Patents (<https://patents.google.com/>), which showed 305 Type 1 Nano pesticide patents and 858 Type 2 patents, some of which are

projected to hit the market very soon or are already on the market (for example, Nu-Clo silvercide (EPA registration number 7124-101, approved in 2007) and DuPont Kocide 3000 (EPA registration number 352-662, approved in 2007) in which nano-Ag and nano-Cu(OH)₂ are the AIs, respectively).

2. Nanoparticles in Drought-Stress Tolerance

Drought is regarded as the most detrimental environmental stress, reducing crop yield more than any other. According to the Intergovernmental Panel on Climate Change (IPCC), the average temperature will rise by 1.8 to 4.0 °C by 2100, and drought will affect vast areas of the world (Ozturk, M.; Unal,

B.T.; García-Caparrós, P.; Khursheed, A.; Gul, A.; Hasanuzzaman, M.,2020). Drought affects agriculture when plants have insufficient moisture to develop normally and complete their life cycles. The severity of drought is further increased by a

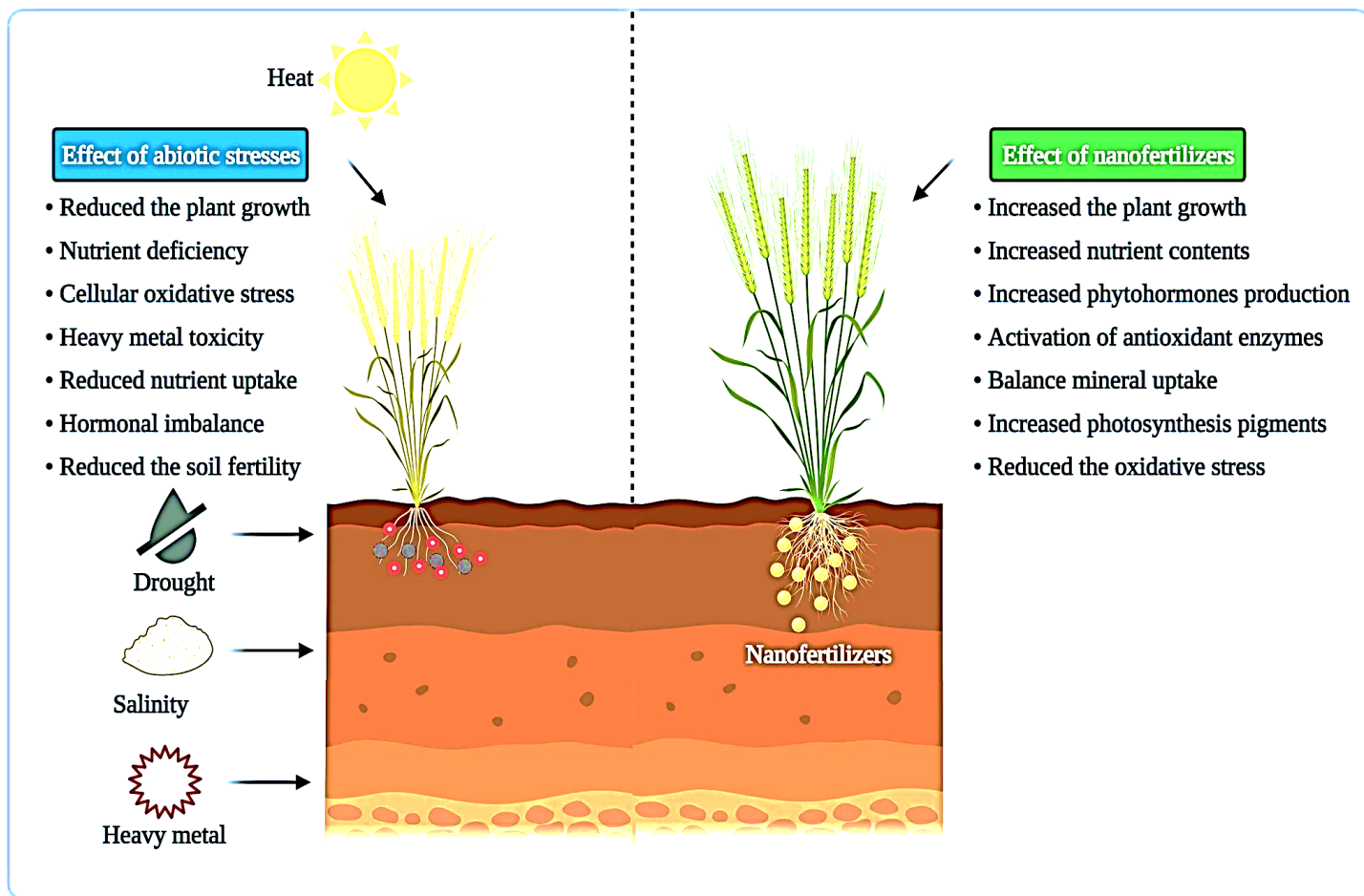


Figure 12: The positive effect of nanoparticles (NPs) on plant growth and development under abiotic stress conditions.

continuous decline in precipitation and increase in evapotranspiration demand (Farooq, M.; Hussain, M.; Wahid, A.; Siddique, K.H.M.,2012).For instance, drought stress prevents plant development, because water is required for cell turgor, which is the pressure that a contained liquid exerts on cell walls, causing cells to expand (Zhang, H.; Zhao, Y.; Zhu, J.-K.,2020). The principal effects of drought on crop plants include slower rates of cell division and growth, smaller leaves, longer stems and roots, disordered stomatal oscillations, altered water and nutrient relationships with lower crop output and inefficient water usage (Farooq, M.; Hussain, M.; Wahid, A.; Siddique, K.H.M.,2012).

As per previous studies, NPs cause a variety of morphological, physiological and biochemical changes in plants as they increase their resistance to drought stress by increasing plant root hydraulic conductance and water uptake and demonstrate a differential abundance of proteins involved in oxidation-reduction, ROS detoxification, stress signaling and hormone pathways (Kandhol, N.; Jain, M.; Tripathi, D.K.,2022). The foliar application of metal-oxide nanoparticles, such as titanium dioxide (TiO₂), zinc oxide (ZnO) and iron oxide (Fe₃O₄), were found to be effective in enhancing the plant's physiological and metabolic activities under drought stress(Alabdallah, N.M.; Hasan, M.; Hammami, I.; Alghamdi, A.I.; Alshehri, D.; Alatawi, H.A.,2021). When Si NPs were applied to drought-

stressed pomegranate plants, additional improvements were made to their photosynthetic pigments, nutrient status, physical and chemical parameters (especially those related to fruit cracking), phenolic content and concentrations of osmolytes, antioxidant enzymes and abscisic acid (Zahedi, S.M.; Hosseini, M.S.; Meybodi, N.D.H.; Peijnenburg, W.,2021). El-Zohri et al. ,2021 suggested that green ZnO-NPs administered topically at lower concentrations could successfully boost tomato tolerance to drought stress. In addition to nano fertilizers, green synthesized Fe₃O₄ NPs were also found to be effective in reducing the impact of drought stress on fenugreek plants (Bishta, S.; Sharma, V.; Kumari, N. ,2022). However, a study by Potter et al.,2021 indicates that the potential benefits of using NPs in enhancing plant drought resistance only actualize under specific environmental circumstances.

3. Nanoparticles in Cold-Stress Tolerance

Global climate change also contributes to cold or low-temperature stress, which harms plant growth and development. Plants often experience two types of low-temperature stress: chilling and freezing. Chilling temperatures for plants range from 0 to 15 °C, depending on the species and tolerance level of the plant. The air temperature and wind speed during exposure are other factors that affect chilling temperatures. In contrast to its response to chilling temperatures, the plant will battle against freezing temperatures (below 0 °C) (Aslam, M.; Fakher, B.; Ashraf, M.A.; Cheng, Y.; Wang, B.; Qin, Y. ,2019). Crop species can be hurt or killed by low and nonfreezing temperatures, which can have an impact on their productivity, survival and ecological dispersion(Adhikari, L.; Baral, R.; Paudel, D.R.; Min, D.; Makaju, S.O.; Poudel, H.P.; Acharya, J.P.; Missaoui, A.M.,2022) As enzyme and other-protein activity are reduced at colder temperatures, cold stress slows down plant growth (Zhang, H.; Zhao, Y.; Zhu, J.-K.,2020). Numerous processes in these plants are impacted by low temperatures, including those involved in secondary metabolism, respiration, defense and protein and nucleic acid production(Aslam, M.; Fakher, B.; Ashraf, M.A.; Cheng, Y.; Wang, B.; Qin, Y. ,2022).

Chitosan nanoparticles and TiO₂ NPs have been used extensively in a variety of studies for their efficiency in cold-stress tolerance. The application of Ti NPs was found to be effective in improving electrolyte leakage, photosynthetic activity and membrane damage under cold-stress conditions in chickpea plants using transcriptional regulation (Mohammadi, R.; Maali-Amiri, R.; Abbasi, A.2013; Mohammadi, R.; Maali-Amiri, R.; Mantri, N.,2014; Amini, S.; Maali-Amiri, R.; Mohammadi, R.; Shahan Dashti, S.-S.K.,2017). Hasanpour, H.; Maali-Amir, R.; Zeinali, H.,2015 suggest that when TiO₂ NPs are applied to plants, the tolerance of chickpea plants to cold stress may develop by controlling the pressure of the temperature drop injury and altered metabolism for plant

growth. The deleterious effects of cold stress are reduced and glycyrrhizin content is enhanced when using TiO₂ NPs in licorice plants (Ghabel, V.K.; Karamian, R.,2020). The use of chitosan nanoparticles was found to be effective in reducing the ROS with the accumulation of Osmo protectants in banana plants under cold-stress conditions (Wang, A.; Li, J.; Al-Huqail, A.A.; Al-Harbi, M.S.; Ali, E.F.; Wang, J.; Ding, Z.; Rekaby, S.A.; Ghoneim, A.M.; Eissa, M.A. ,2021). Furthermore, in rice plants, the foliar application of ZnO NPs may reduce chilling stress through the antioxidative system and transcription factors involved in the chilling response (Song, Y.; Jiang, M.; Zhang, H.; Li, R. ,2021). Similarly, the use of SiNPs can also improve the photosynthetic ability of sugarcane plants under chilling stress (Elsheery, N.I.; Sunoj, V.; Wen, Y.; Zhu, J.; Muralidharan, G.; Cao, K.,2020).

4. Nanoparticles in Heavy-Metal-Stress Tolerance

Heavy-metal (HM) stress is one of the deleterious factors that reduces crop productivity in the modern day. Human activities, such as industrialization and urbanization, have resulted in HM pollution all over the world (Emamverdian, A.; Ding, Y.; Mokhberdorran, F.; Xie, Y.,2015). Enhanced implementation of modern agricultural tools, such as chemical pesticides and fertilizers, has also contributed to HM stress in crop plants. Heavy metals such as Hg, Pb, Cd, Ni, Co, Cr and Ag have deleterious impacts on plants (Yadav, S.K.,2010). Since plants reside at the baseline of trophic systems, the chances of bioaccumulation of these HMs via the food chain are high, and this eventually leads to chronic health impairments, such as kidney and liver damage, in humans and other animals. In addition, HMs have a direct impact on plants, such as through morphological and physiological abnormalities and impaired metabolic pathways (Tiwari, S.; Lata, C. ,2018). These affect the quality and quantity of plant-based products, especially in agricultural crops and medicinal plants.

A number of studies on the use of nanoparticles to alleviate HM stress have been conducted. Nanoparticles applied to the soil can absorb and transform the HMs in soil, thereby reducing the bioaccumulation and mobility of HMs. The Cd metal availability in soil has been reduced by the application of Fe₃O₄ NPs (Wang, Y.; Liu, Y.; Zhan, W.; Zheng, K.; Lian, M.; Zhang, C.; Ruan, X.; Li, T.,2020). The hydroxyapatite NPs can reduce the toxic effects of metals in soil and can maintain the soil pH by releasing phosphate ions (Cui, H.; Shi, Y.; Zhou, J.; Chu, H.; Cang, L.; Zhou, D.,2018). NPs also induce the formation of apoplast barriers, which reduce the heavy-metal content in the root. Furthermore, heavy metals can be intercepted by the regulation of metal transporter genes in plants using specific NPs, which can deter the translocation of HMs by forming complexes with them (Wang, K.; Wang, Y.; Wan, Y.; Mi, Z.; Wang, Q.; Wang, Q.; Li, H.,2021). NPs such as SiNPs have endorsed the production of organic acids that

curtail the damage of HM stress (Cui, J.; Liu, T.; Li, F.; Yi, J.; Liu, C.; Yu, H.,2017; Wu, H.; Tito, N.; Giraldo, J.P.,2017). NPs also activate the antioxidant system, thereby reducing the stress caused by ROS (Wu, H.; Tito, N.; Giraldo, J.P.,2017). Most plants are sensitive to flooding as a result of excessive water clogging in soil. Flooding is caused either by excessive rainfall, poor soil drainage or irrigation practices. The complete

submersion of plants in floodwater can be disastrous for crops. Flooding is thus one of many abiotic-stress factors that affect food availability and countries' economies. It influences the plants grown in different ecosystems, such as floodplains, riparian zones, salt marshes, tidal zones and wetlands.

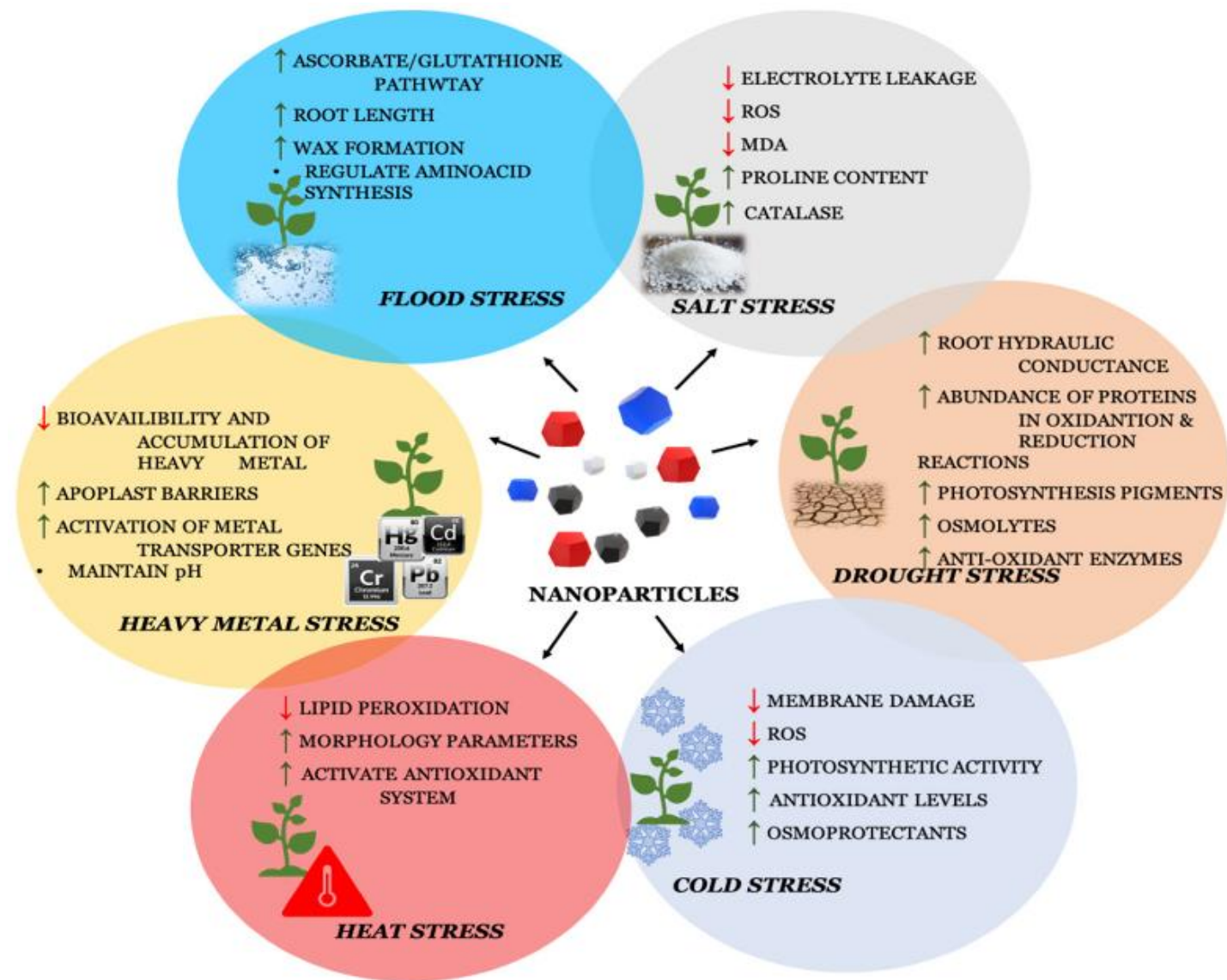


Figure 13: Nanoparticles involved in combating abiotic stress.

. Plants grown in different ecosystems show varied responses to flooding stress; wetland plant species show tolerance to shoot submergence and soil water logging, while dry-land species are sensitive to flooding stress.

5. Nanoparticles in Flooding-Stress Tolerance

Excessive water logging in air spaces delays the exchange and diffusion of gas between the roots (rhizosphere) and the atmosphere, thereby inhibiting respiration due to a lack of oxygen leading to hypoxia and ultimately leading to anoxia in plants. Under flooding stress, soil pH and redox potential will

be affected, the carbon-dioxide content increases and the mobilization of phytotoxins increases, affecting the root metabolism, nutrient uptake and overall plant growth (Bailey-Serres, J.; Colmer, T.D. ,2014).

Nanoparticles have been reported to alleviate flooding stress in plants. In soybean plants under flooding stress, silver NPs helped to alleviate stress conditions by regulating amino-acid synthesis, proteins, glycolysis and wax formation, and NPs enhanced the growth of soybean plants despite stress (Mustafa, G.; Sakata, K.; Komatsu, S.,2015; Mustafa, G.; Sakata, K.;

Komatsu, S., 2016). Another study has been conducted into soybean plants under flooding stress, where Al₂O₃ NPs were applied to ameliorate the growth impairment induced by flood stress. The Al₂O₃ NPs increased root length, including that of the hypocotyl, suppressed the proteins involved in glycolysis, arbitrated the cells involved in the scavenging of ROS by upregulating the ascorbate/glutathione pathway (AsA/GSH) and increased the ribosomal proteins (Mustafa, G.; Komatsu, S., 2016).

6. Nanoparticles in Heat-Stress Tolerance

High temperatures can cause heat stress. In recent decades, global warming has worsened this trend. The rise in temperature above a critical limit for a longer time sufficient to permanently harm plant development is often understood to constitute heat stress (Hu, S.; Ding, Y.; Zhu, C., 2020). Extreme changes may damage the intermolecular connections required for optimal growth during hot summers, which would hinder plant development and fruit set (Bitá, C.E.; Gerats, T., 2013). In general, heat stress decreases the effectiveness of photosynthetic processes, shortening the plant life cycle and lowering productivity (Zhao, J.; Lu, Z.; Wang, L.; Jin, B., 2020). Heat stress may become a significant issue restricting field-crop productivity in tropical and subtropical areas. The application of Se NPs in sorghum plants exposed to high temperatures was found to be helpful in ameliorating negative

impacts, such as membrane damage and reduced pollen germination and crop yields, by activating the antioxidant defense system (Djanaguiraman, M.; Belliraj, N.; Bossmann, S.H.; Prasad, P.V.V., 2018). The application of AgNPs shielded wheat plants from heat stress by enhancing morphological growth (Iqbal, M.; Raja, N.I.; Mashwani, Z.-U.; Hussain, M.; Ejaz, M.; Yasmeen, F., 2019). Similar to this, Zn nanoparticles were discovered to be helpful in improving wheat's ability to withstand heat stress by increasing the production of antioxidant enzymes and decreasing lipid peroxidation (Hassan, N.S.; El Din, T.A.S.; Hendawey, M.H.; Borai, I.H.; Mahdi, A.A., 2018). The foliar application of nanoparticles on tomato leaves becomes activated when the temperature exceeds certain limits and protects plants from heat stress. Si NPs are also said to be helpful in coping with heat stress (Kim, Y.-H.; Khan, A.L.; Waqas, M.; Lee, I.-J., 2017).

II. Mechanisms of Action of NPs in Plants

Although NPs have a wide range of applications in agriculture, the majority of NPs are hazardous to plants when present in high concentrations. The uptake, accumulation and interference of NPs with key metabolic processes in different plant tissues may have positive or negative effects on plants, depending on their dosage, movement, characteristics, and reactivity.

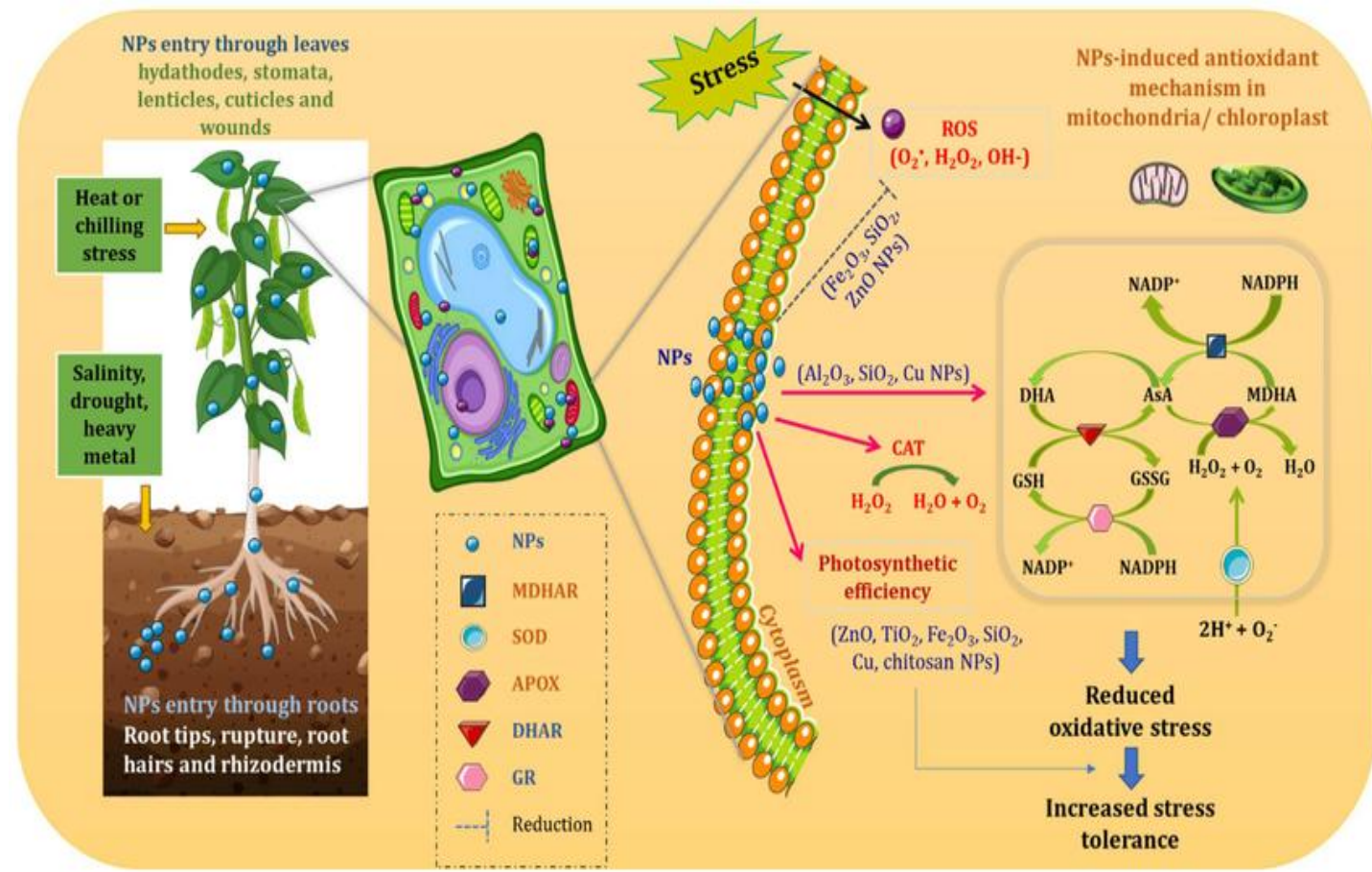


Figure 14: Antioxidative mechanism of action of nanoparticles in plants under abiotic stress (NPs: nanoparticles; MDHAR: monodehydroascorbate reductase; SOD: superoxide dismutase; APOX: ascorbate peroxidase; DHAR: dehydroascorbate reductase; GR: glutathione reductase; ROS: reactive oxygen species).

1. Uptake of NPs

High concentrations of NPs can penetrate plant cells and cross the plasma membrane; thus, this may interfere with key cellular activities (Mazumdar and Ahmed, 2011; Mirzajani et al., 2013). NPs can reach plant tissues through the root system or above-ground parts such as root junctions and wounds. As carriers, NPs must pass through several physiological barriers until they are taken up by the plant and translocated. Plant cell walls, which are made up of cellulose, allow small NPs, ranging between 5 and 20 nm in size, to pass through into the plant cells (Dietz and Herth, 2011). Some NPs have been shown to develop larger pores in the cell wall to enter the cell (Navarro et al., 2008; Kurepa et al., 2010). NPs can be transferred to other plant tissues *via* the apoplastic and symplastic pathways (Etxeberria et al., 2006; Ma et al., 2010). Wong et al. (2016) suggested a lipid exchange mechanism for NPs transport into plant cells. The size, magnitude, and zeta potentials of NPs are important to determine their delivery in plant cells. Application of NPs Under Salinity Conditions: NPs application is important to mitigate the abiotic stress effects of salinity on plants. At the germination stage, the use of Ag NPs in *Lathyrus sativus* under salt stress improves germination percentage, shoot and root length, and seedling FW and DW; thus, this enhances osmotic regulation and reduces the negative effects associated with salinity (Hojjat, 2019).

Noman et al. (2020) found that applying Cu NPs to the soil reduced oxidative stress in wheat and significantly increased plant development and yield. The use of NPs in wheat not only enhances plant development but also improves germination performance under salt-stress conditions (Shi et al., 2016). Preapplication of Ag NPs to wheat seeds alters antioxidant enzyme activities, reduces oxidative damage, and elevates salt-stress tolerance in such plants (Kashyap et al., 2015). In addition, ZnO NPs are known to increase the DW of sunflowers under salt stress (Torabian et al., 2016). CeO NPs (100 and 200 mg kg⁻¹) was found to enhance the physiological responses of *B. napus* under salt stress (100 mM NaCl). CeO NPs are also known to boost plant biomass in salt-stressed canola (Rossi et al., 2016). The application of Ag NPs to basil seeds under salt-stress conditions increases seed germination (Darvish Zadeh; Hojjat and Kamyab, 2017). Ag NPs applied to *S. hortensis* increase plant resistance to salt stress while reducing salt-stress-induced effects on germination percentage and plant shoot length (Nejatzadeh, 2021). Furthermore, the use of Ag NPs in salt-stressed cumin plants substantially improves plant salt resistance (Ekhtiyari and Moraghebi, 2012). Finally, Askary et al. (2017) reported that Fe₃O₄ NPs protects

mint plants from oxidative stress caused by increased NaCl content.

1.1. Application of NPs Under Drought Conditions

Drought is considered a major abiotic stress that can drastically limit crop production (Al-Ashkar et al., 2021; Roy et al., 2021). NPs application is an efficient method for alleviating the impact of drought on plants by increasing antioxidant enzyme activity, improving phytohormone levels, and affecting physiological properties. The use of analcite NPs in soil under hot, dry conditions has been shown to promote germination and plant growth in wheat (Hossain et al., 2021). In addition, the use of ZnO NPs in soybean seeds under arid conditions increases the germination percentage of the seeds (Sedghi et al., 2013). Under drought stress, the use of Cu and Zn NPs in wheat plants increases their antioxidant enzyme activity and relative moisture content, decreases thiobarbituric acid levels, affects reagent precipitation, stabilizes photosynthetic pigment levels in leaves, and reduces the effects of stress (Taran et al., 2017; Semida et al., 2021). In response to drought stress, SiO₂ NPs application can increase shoot length and relative water content (RWC) in barley, while reducing superoxide radical formation and membrane damage (Turgeon, 2010).

Jaber Zadeh et al. (2013) have reported that foliar usage of TiO₂ NPs in wheat is effective to overcome the yield reduction caused by drought stress. Furthermore, the application of Cu NPs to maize increased leaf water content, plant biomass, and anthocyanin, chlorophyll, and carotenoid contents under arid conditions (van Nguyen et al., 2022). Ashka and et al. (2015) reported that SiO₂ NPs applied to hawthorn grown under drought stress reduced photosynthesis and stomatal conductivity. However, silicon (Si) NPs have been reported to ameliorate the effects of drought stress in bananas (Mahmoud et al., 2020). Under moderate drought conditions, foliar application of Si NPs to coriander resulted in optimum antioxidant capacity and essential oil yield (Afshari et al., 2021). Shallan et al. (2016) have reported that foliar application of SiO₂ and TiO₂ NPs can reduce the negative effects of drought stress on cotton plants under arid conditions. In chickpea plants, the application of Si NPs to the soil reduces the negative effects of drought by increasing the relative moisture content in the plants (Gunes et al., 2007). Si- and selenium (Se)-NPs can reportedly help in enhancing growth, improving ion selectivity in roots, and increasing the yield of rice under saline conditions (Badawy et al., 2021). Although drought stress increases the adverse effects of Cd in wheat, the application of

ZnO NPs can reduce both Cd and drought stress (Khan et al., 2019).

1.2. Application of NPs Under Heavy Metal Stress Conditions

Under HM's stress conditions, soil or foliar applications of NPs can eliminate the adverse effects of stress, improve plant development and photosynthesis, and reduce oxidative stress-induced toxicity. Therefore, the application of NPs contributes to in the remediation of HMs-contaminated environments. Under HMs stress conditions, the application of NPs to plants reduces the concentration of HMs in the soil, regulates the expression of HMs transfer genes in plants, increases the activity of plant antioxidant systems, improves physiological functions, and stimulates the production of protective substances such as root secretions, phytochelatin, and organic acids (Rui, 2021). The application of Si NPs on maize plants under arsenic (As) stress reduced the total chlorophyll, carotenoid content, and total protein content, in addition to mitigating the adverse effects of As stress on maximum quantum efficiency, photochemical quenching, and non-photochemical quenching of FS II (Tripathi et al., 2016). Soil application of TiO₂ NPs can effectively limit Cd toxicity by enhancing the physiological parameters and photosynthetic rate in soybean plants; therefore, TiO₂ NPs are vital to mitigate the effects of HMs-induced oxidative stress (Singh and Lee, 2016). When treated with SiO₂ NPs, the activities of enzymes, such as ascorbate peroxidase (APX) and superoxide dismutase (SOD), increased, whereas the effects of oxidative stress were reduced in pea seedlings under Cr stress (Tripathi et al., 2015b). Furthermore, de Sousa et al. (2019) revealed that Si NPs can reduce Al toxicity by activating the antioxidant defense mechanism in maize plants. Konate et al. (2017) found that Fe₃O₄ NPs protected wheat against Cd-induced oxidative stress. Foliar applications of Se NPs to Chinese cabbage under Cd stress increased the biomass, plant height, leaf chlorophyll content, SOD levels, and plasma glutathione peroxidase (GPX) content, whereas the Cd and malondialdehyde (MDA) contents of the leaves were reduced (Zhang, 2019). Similarly, Si NPs alleviate the effect of Cd stress in rice (Wang et al., 2015). The combined use of foliar ZnO NPs and soil biochar in plants was found to be more effective against Cd stress (Rizwan et al., 2019a). Similarly, the co-application of Fe NPs and biochar reduced the effects of Cd stress in rice (Hussain et al., 2019c). The use of FeO NPs in Cd-stressed wheat reduced the leaf electrolyte leakage ratio and Cd content in grains, while improving the antioxidant enzyme action and DW of the plants. Foliar application of Fe NPs is preferable over soil usage. Rahmati Zadeh et al. (2019) also found that 20 mg L⁻¹ of Fe₃O₄ NPs reduced Cd accumulation and improved Cd toxicity by increasing nutrient uptake in tomato plants.

5. Nano Fertilizers Versus Commercial Fertilizers

Agrochemicals can be released in a controlled manner, and macromolecules can be delivered selectively. By incorporating nanoscale transporters and chemicals, the efficient use of fertilizers and pesticides can be improved, resulting in a reduction in the amount used without compromising the yield of crops. In contrast, commercial fertilizers provide fewer benefits to plants because of their larger particle size and reduced solubility. In addition, repeated chemical fertilizer application results in a toxic build-up of HMs that disrupts the ecological balance in the soil. In addition, excessive application of chemical fertilizer can contribute to soil pollution due to leaching or not being fully utilized by plants; thus, the remainder is converted into insoluble salts in the soil.

Nano agrochemicals play an important role in enhancing nutrient use efficiency and water quality management for sustainable agriculture. However, bioaccumulation and long-term exposure of NPs to plants may have a negative impact on edible plants and food chains (Rajput et al., 2020). According to Staroń et al. (2020), NPs can be taken up and deposited in the edible tissues of crop plants. The accumulation of NPs or metal ions in their natural state can disrupt plant physiological activities, affect the integrity of cellular and subcellular organelle organizations, and modify the content of proteins, lipids, and nucleic acids by creating hydroxyl radicals (Cota-Ruiz et al., 2018; Rajput et al., 2020). Overall, the wide-ranging applications of NPs may generate a slew of difficulties from an ecological, ethical, health, and safety standpoint (Rajput et al., 2018).

Until now, the potential negative effects of NPs on human health have been speculative and unsubstantiated (Staroń et al., 2020). By developing various NPs as new tools for the agriculture industry, nanotechnology has grown in popularity. There is an urgent need to increase our knowledge and understanding of the specific benefits and drawbacks associated with the use of NPs. The advancement of nanotechnology has resulted in significant amounts of manufactured NPs in the agri-environment. Although this technology has numerous advantages, researchers and experts are concerned about the unsafe disposal of NPs in large quantities (several hundred tons) each year (Rajput et al., 2020). The existence of NPs in various controlled objects (atmospheric air, water objects, soils, hydrobionts, algae, fungi, tissues of land plants/animals) is recommended (Rajput et al., 2020). In comparison with other sources, the fate and movement of NPs in soil have undergone very little research. Simultaneously, the soil offers fundamental nutrients to food crops, which can also operate as NPs collector sink (Rajput et al., 2020). The current review sheds light on the potential impact of NPs on the environment, health, and food security.

Examples of NPs and the Roles They Play in Relieving Stress in Plants

5.1. Si NPs

Si-based materials and their oxides are found abundantly in the soil. Plants naturally contain high levels of Si (1–10%) as well. Si in plants is found in the form of amorphous silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) in the cell wall, providing it with strength and solidity, in addition to contributing to polyphenols and pectins as a reactant (Bhatt and Sharma, 2018). These substances are also active during plant defense and development. Because of their application in multiple agricultural fields, it has been reported that Si-based NPs can ameliorate abiotic stresses (Jeelani et al., 2020). However, little is known about the mechanisms by which Si alleviates stresses in plants (Ma, 2004; Liang et al., 2007; Datnoff et al., 2009). Si particles and Si NPs can increase tolerance to abiotic stress, nutrient element homeostasis, stimulation of antioxidant enzymes, and improved absorption, immobilization, and partition of metal ions (Liang et al., 2007; Monica and Cremonini, 2009; Qados, 2015). SiO_2 NPs considerably enhance germination, development, and yield in plants under stress. This can be attributed to the uptake of these NPs *via* roots leading to the development of a thin layer in the cell wall helping plants to tolerate various stresses (DeRosa et al., 2010; Siddiqui et al., 2014). SiO_2 NPs also increase the efficiency of water translocation, increase turgor pressure, and enhance relative water inclusion in leaves and water usage effectiveness in plants (Rawson et al., 1988; Wang and Naser, 1994). Sharifi-Rad et al. (2014) found that various concentrations of SiO_2 NPs significantly promoted maize growth and affected different developmental stages. SiO_2 NPs can also be involved in the regulation of protein and phenolics, which are important for the growth and development of *Zea mays* (Suriyaprabha et al., 2012). In addition, they found that a relatively high level of Si accumulated in roots would boost drought tolerance in maize.

Precipitated Si NPs within plant tissues are capable of increasing the expression of essential biochemical elements, improving development, and enhancing yield factors in maize (Suriyaprabha et al., 2012). Furthermore, the improved action of the enzymatic system, the build-up of nutrients, free Pro, amino acids, and water absorption are positive effects of NPs that improve stress tolerance in crops (Wang et al., 2015; Shalaby et al., 2016; Shojaei et al., 2019). Importantly, Si NPs can also increase plant tolerance to drought stress. Ashkavand et al. (2015) observed enhanced drought tolerance as well as retention of critical biochemical and physiological attributes in hawthorn seedlings following the application of SiO_2 NPs under different levels of drought stress. Pretreatment with SiO_2 NPs positively influences the photosynthetic rates, stomatal conductance, and augmented xylem water potential in hawthorn seedlings under drought stress. Large dosages of SiO_2 NPs supplied with irrigation water before drought treatments mitigate drought stress effects

on growth and biochemical and physiological parameters of *Prunus mahleb* (Tripathi et al., 2015b). Improved drought tolerance, evident by an improvement in root development and retention of the photosynthetic ratio, was also reported in two cultivars of *S. bicolor* with varying drought sensitivities after the application of Si NPs. Thus, increase in drought resistance occurred regardless of the cultivar sensitivity to drought stress (Hattori et al., 2005).

Pei et al. (2010) noted that the use of an appropriate concentration of sodium silicate (i.e., 1.0 mM) could moderately diminish the negative effects of drought stress in wheat. In the same study, there was partial promotion of shoot development and chlorophyll content when Si was supplied. This also helped retain leaf water potential and reduced membrane lipid peroxidation in stressed plants (Pei et al., 2010). Under drought stress, Si deposition in plant cells could help reduce the transpiration ratio, and enhance the photosynthesis mechanism (Ali et al., 2012; Siddiqui et al., 2014). Thus, the effects of drought stress can be mitigated by various Si/ SiO_2 NPs applications in various plant species (Zargar et al., 2010). The improved performance of such NPs can be attributed to the increased absorption and/or penetration into plant tissues; however, the exact mechanisms are not yet understood (Ashkavand et al., 2015). Shallan et al. (2016) have reported that foliar sprays of TiO_2 NPs (50 mg L⁻¹) or SiO_2 NPs (3200 mg L⁻¹) increase the drought tolerance of cotton plants. In addition, Si can help plants acclimatize to various ecological stresses (Rastogi et al., 2019). Salinity stress restrains crop yield because of Na^+ ion toxicity in approximately 23% of planted areas worldwide (Onaga and Wydra, 2016). However, the application of Si NPs and Si fertilizer under salinity stress has positive impacts on the physiological and morphological indices of vegetative characteristics in *O. basilicum*. This is evident from the remarkable enhancement in the developmental index, chlorophyll content, and Pro concentration. This, may be because of the involvement of NPs and Si fertilizers with increasing tolerance to salinity stress in plants (Kalteh et al., 2014). The use of SiO_2 NPs has also been shown to enhance developmental parameters, chlorophyll content, Pro accumulation, and upregulation of antioxidant enzyme activity in tomato and squash plants under salinity stress (Haghighi et al., 2012; Siddiqui et al., 2014).

The application of SiO_2 NPs improves not only seed germination and early seedling development but also other related characteristics in lentil genotypes under salinity stress. Thus, SiO_2 NPs boost salt toxicity protection in plants (Sabaghnia and Jan Mohammadi, 2014). SiO_2 NPs can also mitigate stress by reducing Na^+ ion concentration, resulting in improved crop development, production, and survival under salinity stress (Savvas et al., 2009). The application of SiO_2 NPs also increases FW in maize in response to salinity stress (Gao

et al., 2006). Si NPs can improve plant development by reducing osmotic potential and Na^+ toxicity associated with high salt stress (Raven, 1983). It has been reported that SiO_2 NPs form a layer in the root cell wall that enables plants to tolerate several stresses (e.g., salinity) (DeRosa et al., 2010; Abdel Latef et al., 2018).

Wang et al. (2010) and Wang X. et al. (2011) and others have documented the capability of Si and SiO_2 NPs in reducing the harmful effects of salt on plant development. Because of their small size, up taking SiO_2 NPs can be performed more efficiently than up taking micro- SiO_2 , $-\text{Na}_2\text{SiO}_3$, or $-\text{H}_4\text{SiO}_4$ when added to maize roots and seeds (Suriyaprabha et al., 2012). The particles were subsequently used by plants to improve growth by affecting xylem humidity, water translocation, and increasing turgor pressure; which in turn, improves the RWC and water use efficiency (WUE). The enhancement of plant germination and developmental traits by SiO_2 NPs may be associated with an enhanced K/Na ratio, which reduces Na^+ uptake (Alsaedi et al., 2018), and increases the expression of antioxidant enzymes (Torabian et al., 2016; Farhangi-Abriz and Torabian, 2018). According to Almutairi (2016a), it has been found strong interactions between the enhancement of seed germination and growth in tomato-stressed plants with high salt and the increased expression of salt tolerance genes when Si NPs are applied. In contrast to no treatment of Si NPs, *Capsicum annuum* plants showed increased growth when irrigated with saline water upon the application of Si treatments (Tantawy et al., 2015). Several studies have demonstrated that nano-Si is effective in detoxifying HMs or reducing their toxic effects while promoting plant development under HMs stress (Shen et al., 2014; Keller et al., 2015). For instance, the toxicity of Cr in pea seedlings was alleviated by supplementing the growth media with Si NPs, which reduced oxidative stress by decreasing the precipitation of Cr and increasing antioxidant mechanisms (Tripathi et al., 2015a,b). In addition, Cui et al. (2020) have reported that SiO_2 NPs application can reduce oxidative stress in As-exposed rice cell lines. Similarly, the foliar application of 2.5 mM nano-Si can markedly increase tolerance to Cd stress in rice through the regulation of Cd precipitation (Wang et al., 2015).

Si NPs have also been shown to alleviate toxicity caused by Pb, Cu, Zn, and Cd HMs, and their use may be more effective at reducing HMs accumulation compared with traditional strategies (Wang et al., 2016). Liu and Lal (2015) demonstrated that Si NPs are more effective than bulk Si in reducing the detrimental effects of Pb on rice development. Si NPs prevent Pb movement from the rice roots to the shoots and reduce Pb precipitation in grains, especially in high-Pb-precipitating cultivars and in soils with high levels of Pb contamination. Si NPs can also reduce and chelate active HMs ions, stimulate

antioxidant systems, enhance the complexation and coprecipitation of toxic metals with Si, and produce fundamental changes in plants by controlling the expression of metal transport genes. However, these processes are dependent on plant genotypes, plant species, metal elements, developmental requirements, and the duration of stress enforced. Therefore, Si-mediated reductions in metal toxicity might be generalized with caution (Adrees et al., 2015). According to studies conducted by Tripathi et al. (2015b), Si NPs are linked with mitigating the toxicity effects of Cr in *Pisum sativum* seedlings. Cr stress induces toxicity; however, Si NPs can protect pea seedlings from Cr (VI)-induced phytotoxicity by reducing Cr precipitation, enhancing the antioxidant defense system, and alleviating oxidative stress. Tripathi et al. (2016) have also evaluated the effects of Si NPs on alleviating as toxicity in a maize cultivars and hybrids. Hydroponic trials have shown that these NPs can considerably reduce as toxicity by increasing the levels of metabolites of the ascorbate–glutathione cycle, and decreasing the levels of oxidative stress indicators, resulting in reduced As precipitation in the Si NP-treated cultivars and hybrids. It has been hypothesized that Si NPs can be more effective than bulk Si particles for balancing ROS production and ameliorating ROS-mediated damage in treated plants. It has also been reported that Si NPs are more effective than Si in protecting plants against UV-B stress. In general, Si NPs may protect plants by activating their antioxidant defense mechanism and regulating ROS-induced oxidative stress (Tripathi et al., 2017b).

2.5. Ag NPs

Ag NPs are widely used in the agricultural sector, particularly in crop enhancement, food packaging, coating of domestic products, and pesticides. Their use in electronics, drug delivery, and biological-tagging medicine is also relatively common (Bechert et al., 1999; Davies, 2008; Korokin and Rosei, 2008; Jo et al., 2009; Ahamed et al., 2010; Kim et al., 2012). Ag is toxic when used in high concentrations; however, when reduced to a nanosize of 25–50 nm, it has unique properties compared with bulk Ag (Bhatt et al., 2020). Owing to these unique features, Ag NPs can be applied to enhance the vigor of plants and boost their overall development, productivity, and photosynthetic rate (Sharma et al., 2012a; Hatami and Ghorbanpour, 2013; Vannini et al., 2013; Shelar and Chavan, 2015). Ag NPs can also be used as antimicrobial substances to manage diseases on plants (Lamsal et al., 2011). The effect of different concentrations of chemically produced Ag NPs was investigated in *B. juncea* seedlings, specifically on the development and antioxidant status of the plants. Ag NPs were capable of improving growth and inducing the activity of specific antioxidant enzymes, which reduced ROS levels, improved overall antioxidant status, and reduced Pro and MDA levels.

The growth-improving effect of Ag NPs in plants under stress is concentration-dependent; where a 50-ppm dose was ideal to improve growth (Sharma et al., 2012b). In another study on tomatoes, Ag NPs-treated seeds germinated earlier than those treated with deionized water; however, seed germination was inhibited when higher concentrations of Ag NPs were applied (Karami Mehrian et al., 2016).

Ag NPs may also play a role in the expression of stress genes. For instance, the up- and down-regulation of certain genes by Ag NPs was observed in microarray analysis: upregulated genes were mostly associated with responses to metal toxicity and oxidative stress, whereas downregulated genes were associated with responses to microbes and hormonal stimuli (Banerjee and Kole, 2016). Such responses may be associated with plant defense mechanisms under adverse conditions; however, additional studies are required to elucidate the signaling cascades and genes controlled by Ag NPs and other NPs in various plant species.

The effects of Ag NPs on the hydraulic conductivity of the plant stem during drought stress have been studied; however, such NPs might also be capable of entering plant cells and tissues and impairing regular cellular activities (Tripathi et al., 2017a). Hojjat and Ganjali (2016) found that Ag NPs can alleviate the effect of drought stress effects in lentil (*Lens culinaris*). Mahdi Nezhad et al. (2018) reported that Ag NPs can reduce the levels of antioxidant enzymes in plants under drought stress; thus, this reduction can be attributed to the reduced antioxidant metabolism. NPs may be directly involved in the elimination of ROS, which reduces the levels of antioxidant enzymes. Seghatoleslami et al. (2015) reported the effects of Ag NPs on the yields and WUE of drought-stressed *Carum copticum* using a magnetic field.

Ag NPs application is useful to reduce the effect of salinity stress-induced toxicity. This has been demonstrated in studies on the germination of tomato, fennel, and cumin plants treated with Ag NPs; thus, enhancing germination, improving developmental performance, and mitigating the negative effects of salt stress (Ekhtiyari and Moraghebi, 2011; Ekhtiyari et al., 2011; Almutairi, 2016b). Positive effects of different concentrations of Ag NPs suspension have been reported on the germination and development of *Solanum lycopersicum* under salinity stress (Delfani et al., 2014). In the same study, *AREB*, *P5CS*, *MAPK2*, and *CRK1* were induced and *TAS14*, *ZFHD1*, and *DDF2* were repressed when salt-stressed plants were exposed to Ag NPs. A comparative study of the toxicity revealed that Ag NPs or AgNO₃ had negative effects on *C. sativus* seedlings grown at higher concentrations; however, Ag NPs were less toxic than AgNO₃ and had the potential to improve *C. sativus* yield (Cañas et al., 2008). The role of Ag NPs in relieving salt stress in wheat and *B. juncea* has been assessed, and Ag NPs were found to efficiently

alleviate the effects of salinity stress (Sharma et al., 2012b; Mohamed et al., 2017; Abou-Zeid and Ismail, 2018). Ag NPs at 50 and 75 mg L⁻¹ concentrations can protect plants from heat stress and improve their development (Iqbal et al., 2019).

2.3. TiO₂ NPs

TiO₂ is a typical oxide of titanium. As a metal, titanium is abundant in the Earth's crust as well as found in plant and animal tissues. TiO₂ and nano-TiO₂ serve as UV blockers in sunscreens because they diminish the adverse effects of UV radiation. In addition, TiO₂ NPs have photocatalytic sterilizing properties and can undergo redox reactions when subjected to light, resulting in the formation of superoxide anion radicals and hydroxide (Hong et al., 2005). Photo sterilization by TiO₂ NPs can promote photosynthesis and improve plant growth. The potential effects of TiO₂ NPs on the photochemical responses of chloroplasts in spinach (*Spinacia oleracea*) were evaluated (Hong et al., 2005). TiO₂ NPs treatment was found to improve the activities of SOD, catalase (CAT), and peroxidase (POD), decrease the accumulation of reactive oxygen free radicals and MDA levels, and maintain the stability of the membrane structure of chloroplast under the light. TiO₂ NPs also play a role in plant biochemical processes, morphophysiological characteristics, and reactions to various stresses (Mishra et al., 2014). In *S. oleracea*, TiO₂ NPs can increase antioxidant stress tolerance through decreasing superoxide radical precipitation, reducing stress indicator (H₂O₂ and MDA) levels, and stimulating antioxidant enzyme activities within the plants during the photochemical interactions in chloroplasts (Lei et al., 2008).

In spinach plants, nano-anatase TiO₂ treatment markedly increased photosynthesis, electron transmission, photoreduction activity of photosystem II, oxygen evolution, and photophosphorylation of chloroplasts under visible and UV light illumination (Lei et al., 2007, 2008). In addition, the effects of TiO₂ NPs on plant growth have been associated with enhanced photosynthetic rate and nitrogen metabolism (Yang et al., 2006). The photocatalytic degradation of pesticides by TiO₂ has been demonstrated as a possible water remediation process (Lee et al., 2003). Moreover, TiO₂ NPs increase plant water uptake and nitrogen use and stimulate antioxidant activity in canola (Mahmood Zadeh) and wheat (Jaber Zadeh).

Several studies have confirmed the TiO₂ NPs-mediated improvement of plant development. For instance, Changmei et al. (2002) found that TiO₂ and SiO₂ NPs positively affect seed germination and growth of *G. max* (Changmei et al., 2002). In addition, onion seedlings treated with TiO₂ NPs increased the enzymatic activity of SOD, amylase, CAT, and POD (Laware and Raskar, 2014). Mohammadi et al. (2016) explored the potential effects of different concentrations of TiO₂ NPs against drought stress in *Dracocephalum moldavica*. Foliar application

of these NPs at higher concentrations (40 ppm) can reportedly alleviate the detrimental effects of drought stress by adjusting the level of antioxidant enzymes and oxidative stress indicators. TiO₂ NPs have been reported to increase Rubisco activase activity, chlorophyll formation, and the photosynthetic ratio and plant dry mass (Gao et al., 2008). In *Vigna unguiculata*, seed yield increases with foliar application of NPs and TiO₂. Thus, this could be attributed to the increase in photosynthetic rates (Owolade and Ogunleti, 2008). The activity of the antioxidant enzymes (POD and CAT) increases in response to TiO₂ NPs; therefore, MDA precipitation also decreases (Ahmad et al., 2019). The ability of TiO₂ NPs to alleviate the adverse effects of drought stress has been investigated in several studies. For instance, the foliar application of TiO₂ NPs can promote growth and increase the yield of wheat under drought stress when TiO₂ NPs (0.02%) has been used (Jaber Zadeh).

TiO₂ NPs also improved the ability of plants to capture sunlight in maize plants. Under drought stress, TiO₂ NPs can affect the pigment formation, the transformation of light energy to the active electron, and chemical activity, thus, enhancing photosynthetic effectiveness in maize (Akbari et al., 2014). In a similar study, the effects of nano-TiO₂ and -SiO₂ on the biochemical components and productivity yield of drought-stressed cotton plants have also been tested (Shallan et al., 2016). In their findings, the pretreatment with nano-TiO₂ or -SiO₂ can improve the pigment content, antioxidant enzyme activity, and antioxidant capacity, and increase the yield of these plants. The optimum concentrations required to reduce the destructive effects of drought stress in cotton plants were 50 and 3200 ppm for nano-TiO₂ and -SiO₂, respectively. Foliar application of these NPs has also increased drought tolerance in cotton plants. Similar results have been obtained in drought-stressed *L. usitatissimum* treated with TiO₂ NPs (Aghdam et al., 2016). The drought-stressed *D. moldavica* treated with TiO₂ exhibited increased levels of Pro and considerably reduced levels of H₂O₂ and MDA compared with nontreated plants (Mohammadi et al., 2014). Thus, suggesting that TiO₂ NPs can ameliorate stress-induced damage. TiO₂ NPs significantly induced the antioxidant enzyme activity, and Pro and soluble sugar content, which in turn promoted osmotic balance in plant cells and growth recovery in plants (Abdel Latef et al., 2018). *O. basilicum* can tolerate drought stress owing to the combined effects of gibberellin and TiO₂ (Hatami, 2017). Overall, the application of nano-TiO₂ can alleviate stresses of HMs, light, cold, and heat.

Singh and Lee (2016) have shown that the application of TiO₂ NPs can reduce Cd toxicity and enhance the photosynthetic rate in soybean (Singh and Lee, 2016). TiO₂ NPs also play an important role in alleviating light stress. When subjected to light, these NPs catalyzed the redox reaction, thereby generating superoxide anion radicals and hydroxide

(Khan and Siddiqui, 2018). The addition of TiO₂ NPs reduced the impact of heat stress by controlling stomatal opening (Qi et al., 2013). TiO₂ NPs also positively affect plant growth and development. The positive effects of NPs, including TiO₂-NPs, include enhancement of the carboxylation of Rubisco (Gao et al., 2006), light absorption capabilities of chloroplasts (Ze et al., 2011), electron transport rates, and prevention of ROS formation (Giraldo et al., 2014). The use of nano-TiO₂ increases the expression level of genes encoding Rubisco and chlorophyll-binding proteins (Hasan pour) as well as the activity of antioxidant enzymes (Mohammadi et al., 2014); thus maintaining stable contents of chlorophyll and carotenoids, and improving tolerance to cold conditions. Furthermore, TiO₂ NPs positively affect susceptible (ILC 533) and resistant (Sel 11439) genotypes of chickpea under cold stress. Under such stressful conditions, TiO₂ dramatically reduced membrane damage indices, such as ion leakage index and MDA levels, resulting in reduced damage to the membrane (Mohammadi et al., 2013). TiO₂ treatments can also hinder oxidative damage in chickpea and reduce membrane damage under cold stress; suggesting that TiO₂ NPs can ameliorate the redox status under heat exposure (Mohammadi et al., 2014). It has been proposed that TiO₂ NPs improves tolerance to cold stress by enhancing the mechanisms of protection and reducing the levels of injuries in chickpea plants. Future studies may confirm the effectiveness and mechanisms of TiO₂ NPs in improving the tolerance of crops to cold stress.

2.4. Zn NPs

In plants, Zn is a critical micronutrient that regulates metabolic processes and facilitates development (Adhikary et al., 2010; Vitti et al., 2014). Zn also plays an important role in the survival of plants under adverse conditions. Plants use Zn in small amounts; therefore, accessibility of Zn at the nano level ensures that suitable amounts are transported to the plant while avoiding Zn toxicity in the plants and soil. ZnO is an ecofriendly compound that can be used as a “green” element (Pandey et al., 2010). Given its functions in maintaining membrane integrity, retaining the potassium content of cells, and the plant–water relationship, ZnO plays a major role in stomatal regulation (Khan et al., 2004). In a study on chickpeas, Zn deficiency decreased their ability to modulate osmotic pressure under drought stress (Khan et al., 2004). Auxin production can also be affected by Zn *via* the induction of tryptophan synthesis as a precursor for the production of indole acetic acid, which helps in root development and drought tolerance in plants (Waraich et al., 2011). The uptake of Zn can be improved when it is nano-sized; thus, the functions of Zn can be achieved more efficiently when using Zn NPs. The application of Zn NPs enhances radicle development in germinated seeds, and higher Zn content in grains; thereby

improving seed survival and tolerance to environmental stresses, especially in Zn-deficient regions (Cakmak et al., 1996; Degenhardt and Gimmler, 2000; Cakmak, 2008).

Several studies have described the effects of Zn-based NPs on plant development and yield. The use of ZnO NPs, at appropriate concentrations, enhanced biomass production, seed germination, and seedling development in chickpeas, in contrast to the use of bulk ZnSO₄. ZnO NPs can elevate auxin levels, and thus, promote plant development (Pandey et al., 2010; Burman et al., 2013). In another study, the stimulating effect of zinc sulfide (ZnS) NPs on the growth of *B. juncea* has been assessed (Nayan et al., 2016). They showed that chlorophyll content, sugar content, and plant biomass, increased significantly after the application of these NPs, and that the growth-stimulating effects were probably associated with improvements in the plant antioxidant system after ZnS NPs treatment. Furthermore, lower concentrations of ZnS NPs were more effective than higher concentrations in improving plant growth. Similar results have been reported in wheat plants treated with ZnO NPs at 66 mg L⁻¹ (Awasthi et al., 2017). ZnO NPs can mediate the increases in photosynthetic pigments and a concomitant reduction in lipid peroxidation in soil-grown *Coriandrum sativum* plants (Bhatt et al., 2020). Thus, the ZnO-mediated NPs increases the photosynthetic pigments which may help plants cope with stressful conditions by stabilizing ROS generation. Sedghi et al. (2013) have reported that the germination ratio in soybean was potentially augmented by ZnO NPs under water-deficient conditions. Under drought stress, the applied ZnO NPs facilitate the rapid use of seed reservoirs for seedling development and reduced the effects of such stress (Sedghi et al., 2013).

Drought tolerance was also improved by the enhancement of antioxidant enzyme activity in wheat plants via ZnO NPs application (Yang et al., 2018). Both Cu NPs and Zn NPs can improve wheat plant tolerance to drought stress by enhancing the action of antioxidant enzymes and stabilizing the content of photosynthetic pigments (Taran et al., 2017). Seghatoleslami and Forutani (2015) have shown that biomass and WUE have been improved by ZnO NPs in plants under water stress, whereas plants provided with full irrigation achieved strong growth and yield with bulk ZnO treatment. Dimkpa et al. (2017, 2019) have noticed that a composite of ZnO, boric oxide, and CuO NPs can alleviate drought stress in *G. max*. Under drought stress, shoot development and grain production were enhanced by 33 and 36%, respectively, using these NPs; thus, crop productivity and uptake of P and N can be enhanced by the addition of micronutrient NPs. These findings are in agreement with those reported in another study in which ZnO NPs were demonstrated to mitigate drought-induced damage to sorghum productivity, grain fortification, and nutrient acquisition (Dimkpa et al., 2019).

Yang et al. (2018) found that remodeling of root shape by ZnO and CuO NPs could alter drought tolerance in *T. aestivum* plants colonized by *Pseudomonas chlororaphis* O6 (PcO6), a beneficial bacterial species. Zn NPs enhanced the formation of lateral roots, whereas Cu NPs stimulated the propagation of elongated root hairs close to the root tip in wheat seedlings. In the same study, the use of these NPs generally increased the expression of genes related to drought tolerance. In shoots, the expression of other genes, such as those associated with metal stress, increased, and this was consistent with the increases in Cu and Zn concentrations. Thus, plants that were subjected to CuO or ZnO NPs showed cross-protection to multiple challenges, including metal, and drought stress. Despite improvements in root hair formation and production of lateral roots caused by Cu NPs and Zn NPs, respectively, the decreased root length may be the reason for the reduction in water accessibility. In *Arabidopsis* and mustard, the increased lignification because of CuO may alter the water flow and restrict cell wall expansion. Lignification in the cell wall is a plant response that is associated with drought stress and water flow impairment; thus, this may also occur by the binding of Cu ions with cell wall pectins (Nair and Chung, 2014).

When exposed to CuO NPs, anthocyanin and Pro levels increased under water deficient stress. On the addition of CuO NPs, the precipitation of ROS improved in the roots of wheat. The increased levels of ROS and abscisic acid (ABA) due to drought stress may cause transcriptional changes, resulting in subsequent stress tolerance (Dimkpa et al., 2012). Alharby et al. (2016) have investigated the metabolic response of *S. lycopersicum* to ZnO NPs under salinity stress; and they found that the NPs can reverse the adverse effects of salinity stress by regulating tolerance-related proteins/enzymes, mainly through the upregulation of SOD and GPX gene expression. These results are consistent with those of Haripriya et al. (2018), who found that a foliar spray of ZnO NPs mitigates salinity stress effects in finger millet. ZnO NPs treatment in soil-grown sorghum can also improve drought-stress tolerance through the translocation of grain N and the restoration of total N content (Dimkpa et al., 2019). In contrast, ZnO NPs at concentrations ≥ 10 mg L⁻¹ resulted in oxidative stress in tomato plants cultivated in 1/2 Murashige and Skoog media (Rédei, 2008). The differences in results could be attributed to the variation in ZnO NPs, levels of NPs used, plant development media used, and possible variation in plant liability to ZnO NPs.

ZnO NPs also reduced HMs stress by decreasing the uptake of HMs by plants; thus protecting plants from HMs toxicity (Baybordi, 2005; Venkatachalam et al., 2017). The symptoms of oxidative stress caused by Cd and Pb toxicity can be improved by ZnO NPs treatment. In addition, ZnO NPs can improve the total soluble protein and photosynthetic pigment

levels, while reducing lipid peroxidation in developing seedlings of *Leucaena leucocephala* (Venkatachalam et al., 2017). When a foliar spray of ZnO NPs was applied to maize leaves, Cd absorption and Cd-induced oxidative stress were reduced (Rizwan et al., 2019c). Torabian et al. (2016) reported an increase in plant growth, photosynthetic index, and chlorophyll content and a decrease in the Na content in sunflower leaves supplied with ZnO NPs. Similarly, wheat plants treated with CuO/ZnO NPs showed improved growth, which could possibly due to the lower solubility of CuO NPs (Fathi et al., 2017). Taken together, these findings indicated that the application of Zn-based NPs enhanced plant stress tolerance.

6. Nanotechnology-Based Advances in Agriculture

Nanotechnology has several other possible applications and can play an important role in agriculture, forestry, energy production, food processing, environmental management as well as in ensuring water quality and utilizing waste resources (Prasad et al., 2017; Kim et al., 2018). The extensive scope of nanotechnology and its wide range of applications has led to advancements in the agricultural sector (Kim et al., 2018; Shang et al., 2019). Over the last two decades, the use of nanotechnology in agriculture has been supported by research and practical applications at the academic and industrial levels (Shang et al., 2019).

In particular, nanotechnology has been applied to increase crop production. In addition, nanotechnology has been used to produce Nano fertilizers and Nano encapsulated nutrients, which are considered promising methods for achieving site-targeted and regulated delivery of nutrients to plants, thereby improving crop

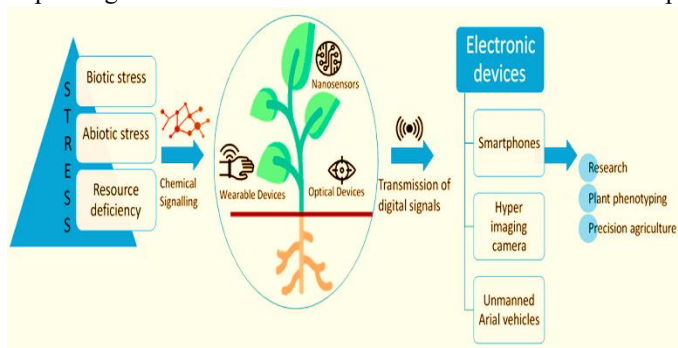


Figure 16: Application of plant based nano sensors in precision agriculture.

production and yield via “precision agriculture.” Nano formulations of agrochemicals, such as Nano pesticides and nano fertilizers, substantially reduce micronutrient losses of fertilizers through volatilization and leaching, enhance effective Phyto availability, feed plants gradually in a controlled manner, and eventually reduce environmental hazards caused by the excessive use of traditional fertilizers (Solanki et al., 2015; Shang et al., 2019; Zulfiqar et al., 2019). Nano fertilizers

can be produced using Cu, SiO₂, Zn, TiO₂, and polymeric NPs as dendrimers acting as nanocarriers (Paramo et al., 2020).

Studies have shown that nano fertilizers can help crop productivity by improving stress tolerance as well as promoting plant germination, growth, and physiological processes. However, nano fertilizers have some drawbacks that have restricted their extensive application (Zulfiqar et al., 2019). Nano sensors have been reported as another application of nanotechnology that can improve crop quality and yield, while ensuring an output of high-quality and healthy food products. Novel nano sensors are primarily applied in crop safety for the detection and management of phytopathogens and for measuring and monitoring the uses, penetration, and residues of agrochemicals as well as environmental pollution (Ion et al., 2010; Chen et al., 2016; Prasad et al., 2017; Paramo et al., 2020). Their use has advanced the human management of soil and plant health, improved food quality, and protection, optimized packaging methods, and enhanced soil monitoring and crop conditions (Kim et al., 2018; Shang et al., 2019). Other agronomic uses of nanotechnology include the use of nanodevices in plant genetic engineering, postharvest management, and plant disease diagnostics (Ion et al., 2010; Prasad et al., 2017). Nanobiotechnology includes the use of novel methods to genetically modify and engineer crop programs that boost agricultural productivity, food safety, and processing capacity while promoting agricultural sustainability. Different methods for the application of NPs in agriculture are shown in Figure 4. The application of nanomaterials enable efficient plant transformation for crop improvement (Anderson et al., 2016; Shafiee-Jood and Cai, 2016). Given their unique properties of small size, multiple binding sites and large surface area, nanomaterials are excellent nanocarriers of bioactive molecules (e.g., plasmid DNA and double-stranded RNA) (de Oliveira et al., 2014; Anderson et al., 2016; Shafiee-Jood and Cai, 2016; Kim et al., 2018; Zhao et al., 2020). Engineered NPs can also be used to increase crop safety and detect pesticide residues (Kim et al., 2018). Moreover, nanotechnology has become a common method used by engineers and designers to enhance and improve soil properties. Nano clay-polymer composites and nano-zeolites can be used in the soil to improve its moisture content, increase water-retention capacity, and slow water release during the cultivation season, and nanomagnets have been used to expel soil contaminants (Vundavalli et al., 2015; Prasad et al., 2017; Kim et al., 2018). The application of nano fertilizers can also help reduce soil toxicity caused by an accumulation of chemical substances applied to the soil, while also acting as an alternative means of enhancing resource-use efficiency (DeRosa et al., 2010; Nair et al., 2010; Jalil and Ansari, 2019). In addition, nano sensors are now widely used in agriculture for soil analysis, water management and transmission, environmental monitoring of

pollution in soils and water, and pesticide and nutrient drop (Ion et al., 2010). Various sensors based on nano detection technology, including biosensors, optical sensors, electrochemical sensors, and other instruments, are important tools for identifying HMs at trace levels (Ion et al., 2010; Prasad et al., 2017; Singhal et al., 2022).

7. NPs-Plant Interaction Pathways

NPs may affect plant metabolism by delivering micronutrients (Liu and Lal, 2015), gene regulation (Nair and Chung, 2014), and interfering with several oxidative processes in plants (Hossain et al., 2015). Excessive contents of NPs can generate ROS; thus, interfering with the oxidative mechanism; while other pathways have yet to be deciphered. The NPs can disrupt the electron transport chain in mitochondria and chloroplast, causing an oxidative burst and an increase in ROS levels (Pakrashi et al., 2014; Cvjetko et al., 2017). The rate of carbon fixation is reduced in response to stressful conditions; thus, this increases photoinhibition, potentially leading to the overproduction of superoxide anion radicals and H_2O_2 in the photosystem (Foyer and Noctor, 2005). When ROS is generated as a result of NPs, all biological components are affected causing protein changes, lipid peroxidation, and DNA damage (Van Breusegem and Dat, 2006). Several studies have found an increase in lipid peroxidation and DNA damage in plants while interacting with NPs (Atha et al., 2012; Saha and Dutta Gupta, 2017). The increase in ROS levels can cause apoptosis or necrosis, resulting in plant cell death (Faisal et al., 2013). Despite its destructive nature, ROS play a role in biological activities, including stress tolerance (Sharma et al., 2012a). The balance between ROS generation and scavenging determines whether ROS has a destructive or signaling function. The cells have developed a robust antioxidant mechanism to precisely control the quantity of ROS. Enzymatic (SOD, CAT, and guaiacol peroxidase) and non-enzymatic (ascorbate, glutathione, carotenoids, tocopherols, and phenolics) antioxidants are attributed to defense mechanisms in plants (Sharma et al., 2012b). Several studies have demonstrated that plants exposed to NPs produce more antioxidant molecules (Jiang et al., 2014; Costa and Sharma, 2016). Plant stress response signaling can also be influenced by phytohormones (Mengiste et al., 2010; O'Brien and Benková, 2013; Sham et al., 2019).

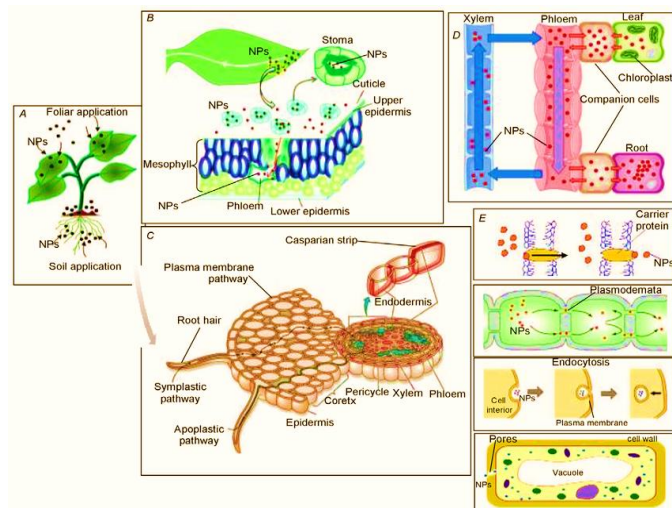


Figure 15: The entry (A) and interaction pathways of nanoparticles (NPs) in plants through roots and leaves (B and C). Long-distance NPs transport via xylem and phloem (D). Probable routes of cellular uptake of the NPs in the plant cell (E).

Plant hormones are endogenous molecules involved in the regulation of plant development and stress tolerance (Sham et al., 2017). In response to abiotic stresses, different hormonal pathways can be activated or suppressed (Kwak et al., 2006; O'Brien and Benková, 2013). In red pepper (*Capsicum annuum*), cytokinin levels increased in response to AgNPs stress; while in cotton (*Gossypium* sp.), a decrease in the levels of auxins and ABA in response to CuO NPs was detected. This suggests that NPs affect plant hormonal balance and plant metabolism.

Several studies have demonstrated that NPs can also affect the content and activity of photosynthetic pigments in plants (Perreault et al., 2014; Tripathi et al., 2017c). High concentrations of NPs have a negative impact on photosynthesis, resulting in growth retardation or death in plants (Tripathi et al., 2017c).

8. Future Prospects on NPs for Enhancing Crop Tolerance to Abiotic Stress

Nanobiotechnology has the potential to improve stress tolerance, stress sensing/detection, targeted delivery and controlled release of agrochemicals, transgenic events, and seed nano priming in plants (Wu and Li, 2022). Such nanomaterials free of HMs and high dispersibility can be developed for agricultural use. Future research on evaluating the biological effects of nanozymes i.e., Mn_3O_4 NPs in plants under stress conditions should be on top of our priorities. Mechanisms underlying nano priming-induced seed germination, breaking seed dormancy, and their interactions with seeds have to be investigated. Understanding how NPs improve plant stress tolerance will enable researchers to design tailor-made nanomaterials targeting agricultural challenges. In addition,

nanomaterials have no doubt a bright future ahead, especially when it comes to their functionality in plants. For example, Santana et al. (2020) have developed a targeted delivery approach using nanomaterials to convert chloroplasts into “chloroplast factory” for better plant photosynthesis under low light conditions. The use of nanomaterials for CRISPR-Cas genome editing in cargo delivery (Demirer et al., 2021) will increase the efficiency of genetic engineering to enhance plant stress tolerance. Developing policies and regulations could help manage biosafety hazards associated with the use of nanomaterials in agriculture. We believe that nanomaterials will play a crucial role in the future of agriculture.

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12. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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14. References:

1. Abdel-Aziz, H. M., Hasaneen, M. N., Omer, A. M. (2016). Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Span. J. Agricul. Res.* 14, e0902–e0902. doi: 10.5424/sjar/2016141-8205
2. Abdel Khalik, A., Pascual-Seva, N., Nájera, I., Domene, M. Á., Baixauli, C., Pascual, B. (2019). Effect of deficit irrigation on the productive response of drip-irrigated onion (*Allium cepa* L.) in Mediterranean conditions. *Hortic. J.* 88, 488–498. doi: 10.2503/hortj.UTD-081
3. Abid, N., Khan, A. M., Shujait, S., Chaudhary, K., Ikram, M., Imran, M., et al. (2021). Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. *Adv. Colloid. Interface Sci.* 300, 102597. doi: 10.1016/j.cis.2021.102597
4. Adhikari, L.; Baral, R.; Paudel, D.R.; 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, 100081.
5. Adrees, M., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., Ur Rehman, M. Z., et al. (2020). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. *Chemosphere* 238, 124681. doi: 10.1016/j.chemosphere.2019.124681
6. Ahmad, J., Bashir, H., Bagheri, R., Baig, A., Al-Huqail, A., Ibrahim, M. M., et al. (2017). Drought and salinity induced changes in ecophysiology and proteomic profile of parthenium hysterophorus. *PLoS One* 12, e0185118. doi: 10.1371/journal.pone.0185118
7. Ahmed, T., Noman, M., Manzoor, N., Shahid, M., Abdullah, M., Ali, L., et al. (2021). Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice *via* triggering the stress responsive genetic mechanisms and nutrient acquisition. *Ecotoxicol. Environ. Saf.* 209, 111829. doi: 10.1016/j.ecoenv.2020.111829
8. Akhtar, N., Ilyas, N., Meraj, T. A., Pour-Aboughadareh, A., Sayyed, R., Mashwani, Z. U. R., et al. (2022). Improvement of plant responses by nano biofertilizer: A step towards sustainable agriculture. *Nanomaterials* 12, 965. doi: 10.3390/nano12060965
9. Alabdallah, N. M., Hasan, M. M. (2021). Plant-based green synthesis of silver nanoparticles and its effective role in abiotic stress tolerance in crop plants. *Saudi. J. Biol. Sci.* 28, 5631–5639. doi: 10.1016/j.sjbs.2021.05.081

10. Alabdallah, N. M., Hasan, M. M., Hammami, I., Alghamdi, A. I., Alshehri, D., Alatawi, H. A. (2021). Green synthesized metal oxide nanoparticles mediate growth regulation and physiology of crop plants under drought stress. *Plants* 10, 1730. doi: 10.3390/plants10081730
11. Alabdallah, N.M.; Hasan, M.; Hammami, I.; Alghamdi, A.I.; Alshehri, D.; Alatawi, H.A. Green Synthesized Metal Oxide Nanoparticles Mediate Growth Regulation and Physiology of Crop Plants under Drought Stress. *Plants* 2021, 10, 1730.
12. Al-Burki, H., Al-Ajeel, S. (2021). Effect of bio-fertilizer and nanoscale elements on root nodules formation and their chemical content of two *Phaseolus vulgaris* l varieties. *Plant Arch.* 21, 1476–1480. doi: 10.51470/PLANTARCHIVES. 2021.v21. S1.232
13. Al-Dhalimi, A. M. A., Al-Ajeel, S. A. H. (2020). Anatomical study on effect of plant growth regulators and zinc nanoparticles in peduncle anatomy of sunflower (*Helianthus annuus* l) plant under water stress. *Ind. J. Ecol.* 47, 7–16.
14. Ali, E., El-Shehawi, A., Ibrahim, O., Abdul-Hafeez, E., Moussa, M., Hassan, F. (2021a). A vital role of chitosan nanoparticles in improvisation the drought stress tolerance in *Catharanthus roseus* (L.) through biochemical and gene expression modulation. *Plant Physiol. Biochem.* 161, 166–175. doi: 10.1016/j.plaphy.2021.02.008
15. Ali, S., Mehmood, A., Khan, N. (2021b). Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *J. Nanomat.* 2021, 6677616. doi: 10.1155/2021/6677616
16. Alsaeedi, A., El-Ramady, H., Alshaal, T., El-Garawany, M., Elhawat, N., Al-Otaibi, A. (2019). Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake. *Plant Physiol. Biochem.* 139, 1–10. doi: 10.1016/j.plaphy.2019.03.008
17. Amini, S.; Maali-Amiri, R.; Mohammadi, R.; Shahan Dashti, S.-S.K. cDNA-AFLP Analysis of Transcripts Induced in Chickpea Plants by TiO₂ Nanoparticles during Cold Stress. *Plant Physiol. Biochem.* 2017, 111, 39–49.
18. Arole, V. M., & Munde, S. V. (2014). Fabrication of nanomaterials by top-down and bottom-up approaches-an overview. *Journal of Material Science*, 1, 89-93.
19. Arslan, E., Agar, G., Aydin, M. (2021). Humic acid as a bio stimulant in improving drought tolerance in wheat: The expression patterns of drought-related genes. *Plant Mol. Bio. Rep.* 39, 508–519. doi: 10.1007/s11105-020-01266-3
20. Asha, A. B., Narain, R. (2020). “Nanomaterials properties,” in *Polymer science and nanotechnology* (Elsevier), 343–359. doi: 10.1016/B978-0-12-816806-6.00015-7
21. Aslam, M.; Fakher, B.; Ashraf, M.A.; Cheng, Y.; Wang, B.; Qin, Y. Plant Low-Temperature Stress: Signaling and Response. *Agronomy* 2022, 12, 702.
22. Avasare, V., Zhang, Z., Avasare, D., Khan, I., & Qurashi, A. (2015). Room-temperature synthesis of TiO₂ nanospheres and their solar driven photoelectrochemical hydrogen production. *International Journal of Energy Research*, 39(12), 1714-1719.
23. Bahri, S. S., Harun, Z., Hubadillah, S. K., Salleh, W. N. W., Rosman, N., Kamaruddin, N. H., et al. (2021). “Review on recent advance biosynthesis of TiO₂ nanoparticles from plant-mediated materials: characterization, mechanism and application,” in *IOP conf. ser. mater. sci. eng*, vol. 1142. (IOP Publishing), 012005.
24. Bailey-Serres, J.; Colmer, T.D. Plant tolerance of flooding stress—Recent advances. *Plant Cell Environ.* 2014, 37, 2211–2215.
25. Behboudi, F., Tahmasebi Sarvestani, Z., Kassaee, M. Z., Modares Sanavi, S., Sorooshzadeh, A. (2018). Improving growth and yield of wheat under drought stress via application of SiO₂ nanoparticles. *J. Agricul. Sci. Tech.* 20, 1479–1492.
26. Bhardwaj M. & Saxena D.C., (2017). Preparation of Organic and Inorganic Nanoparticles and their

- Subsequent Application in Nanocomposites for Food Packaging Systems: A Review, *Indian Journal of Science and Technology*, 10 (31), 1-8
27. Bhaviripudi S., Mile E., Iii S. A. S., Zare A. T., Dresselhaus M. S., Belcher A. M. & Kong J., (2007). CVD Synthesis of Single-Walled Carbon Nanotubes from Gold Nanoparticle Catalysts, *Journal of American Chemical Society*; 129(6):1516-7
 28. Bishta, S.; Sharma, V.; Kumari, N. Biosynthesized magnetite nanoparticles from *Polyalthia longifolia* leaves improve photosynthetic performance and yield of *Trigonella foenum-graecum* under drought stress. *Plant Stress* 2022, 5, 100090.
 29. Bitá, C.E.; Gerats, T. Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. *Front. Plant Sci.* 2013, 4, 273.
 30. Bogutska, K., Sklyarov, Y. P., Prylutsky, Y. I. (2013). Zinc and zinc nanoparticles: biological role and application in biomedicine. *Ukra. Bioorg. Acta* 1, 9–16.
 31. Boisseau, P., Loubaton, B. (2011). Nanomedicine, nanotechnology in medicine. *Com. Ren. Phys.* 12, 620–636. doi: 10.1016/j.crhy.2011.06.001
 32. Cai, W., Gao, T., Hong, H., & Sun, J. (2008). Applications of gold nanoparticles in cancer nanotechnology. *Nanotechnology, Science and Applications*, 1, 17.
 33. Cao, Z., & Dobrynin, A. V. (2016). Nanoparticles as adhesives for soft polymeric materials. *Macromolecules*, 49(9), 3586- 3592.
 34. Chapman, A., Davies, W., Downey, C., Dookie, D. (2021) *ADB climate risk country profile: Micronesia*. ©Asian development bank. Available at: <http://hdl.handle.net/11540/13791>.
 35. Chun, H. C., Sanghun, L., Choi, Y. D., Gong, D. H., Jung, K. Y. (2021). Effects of drought stress on root morphology and spatial distribution of soybean and adzuki bean. *J. Integrat. Agricul.* 20, 2639–2651. doi: 10.1016/S2095-3119(20)63560-2
 36. Churilova, V. V., Nazarova, A. A., Polishchuk, S. D. (2017). Influence of biodrugs with nanoparticles of ferrum, cobalt and cuprum on growth, development, yield and phytohormone status of fodder and red beets. *Nano. Hyb. Comp. Trans. Tech. Publ.* 13, 149–155. doi: 10.4028/www.scientific.net/NHC.13.149
 37. Cui, H.; Shi, Y.; Zhou, J.; Chu, H.; Cang, L.; Zhou, D. Effect of different grain sizes of hydroxyapatite on soil heavy metal bioavailability and microbial community composition. *Agric. Ecosyst. Environ.* 2018, 267, 165–173.
 38. Cui, J.; Liu, T.; Li, F.; Yi, J.; Liu, C.; Yu, H. Silica nanoparticles alleviate cadmium toxicity in rice cells: Mechanisms and size effects. *Environ. Pollut.* 2017, 228, 363–369.
 39. Das, A., Das, B. (2019). “Nanotechnology a potential tool to mitigate abiotic stress in crop plants,” in *Abiotic and biotic stress in plants* (IntechOpen). doi: 10.5772/intechopen.83562
 40. Das, K., Roychoudhury, A. (2014). Reactive oxygen species (ROS) and response of antioxidants as ROS-scavengers during environmental stress in plants. *Front. Environ. Sci.* 2, 53. doi: 10.3389/fenvs.2014.00053
 41. Deka, D. C., Kalita, A., Bardaloi, S., Kalita, M. P. (2019). Influence of capping agent on structural, optical and photocatalytic properties of ZnS nanocrystals. *J. Lumin.* 210, 269–275. doi: 10.1016/j.jlumin.2019.02.033
 42. Dimkpa, C. O., Singh, U., Bindra ban, P. S., Elmer, W. H., Gardea-Torres Dey, J. L., White, J. C. (2019). Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. *Sci. Total. Environ.* 688, 926–934. doi: 10.1016/j.scitotenv.2019.06.392
 43. Dimkpa, C. O., White, J. C., Elmer, W. H., Gardea-Torres Dey, J. (2017). Nanoparticle and ionic zn promote nutrient loading of sorghum grain under low NPK fertilization. *J. Agricul. Food Chem.* 65, 8552–8559. doi: 10.1021/acs.jafc.7b02961

44. Djanaguiraman, M., Nair, R., Giraldo, J. P., Prasad, P. V. V. (2018). Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. *ACS Omega*. 3, 14406–14416. doi: 10.1021/acsomega.8b01894
45. Djanaguiraman, M.; Belliraj, N.; Bossmann, S.H.; Prasad, P.V.V. High-Temperature stress alleviation by selenium nanoparticle Treatment in Grain Sorghum. *ACS Omega* 2018, 3, 2479–2491.
46. Do Espirito Santo Pereira, A., Caixeta Oliveira, H., Fernandes Fraceto, L., Santaella, C. (2021). Nanotechnology potential in seed priming for sustainable agriculture. *Nanomaterials* 11, 267. doi: 10.3390/nano11020267
47. Dong, F.; Yang, F.; Liu, Y.; Jia, W.; He, X.; Chai, J.; Zhao, H.; Lv, M.; Zhao, L.; Zhou, S. Calmodulin-binding transcription activator (CAMTA)/factors in plants. In *Calcium Transport Elements in Plants*; Academic Press: Cambridge, MA, USA, 2021; pp. 249–266.
48. Doolittle, C. L., Mclaughlin, M. J., Kirby, J. K., Navarro, D. A. (2015). Bioavailability of silver and silver sulfide nanoparticles to lettuce (*Lactuca sativa*): Effect of agricultural amendments on plant uptake. *J. Haz. Mat.* 300, 788–795. doi: 10.1016/j.jhazmat.2015.08.012
49. Durán, N., Seabra, A. B. (2012). Metallic oxide nanoparticles: state of the art in biogenic syntheses and their mechanisms. *App. Microb. Biotech.* 95, 275–288. doi: 10.1007/s00253-012-4118-9
50. Durán, P., Acuña, J., Jorquera, M., Azcón, R., Borie, F., Cornejo, P., et al. (2013). Enhanced selenium content in wheat grain by co-inoculation of selenobacteria and arbuscular mycorrhizal fungi: A preliminary study as a potential Se biofortification strategy. *J. Cer. Sci.* 57, 275–280. doi: 10.1016/j.jcs.2012.11.012
51. Dutta, R. K., Nenavathu, B. P., Gangi Shetty, M. K., Reddy, A. (2012). Studies on antibacterial activity of ZnO nanoparticles by ROS induced lipid peroxidation. *Coll. Surf. B.: Bioint.* 94, 143–150. doi: 10.1016/j.colsurfb.2012.01.046
52. Ealia S. A. M., & Saravanakumar M. P. (2019). A review on the classification, characterization, synthesis of nanoparticles and their application IOP Conf. Ser.: Mater. Sci. Eng. 263 03.
53. EDP Sciences. Hasan, S. (2015). A review on nanoparticles: their synthesis and types. *Res. J. Recent Sci*, 2277, 2502. Hosein Nejad, M., Jafari, S. M., & Katouzian, I. (2018). Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Critical reviews in microbiology*, 44(2), 161-181.
54. Elena S. L., Daniela G., Gerard E., Lorena B., Ana L. L. M., Ruth G., Amanda C., Marta E., Miren E., Antoni C., Amélia M. S., Alessandra D., Antonello S., Maria L. G. & Eliana B. S., (2020). Metal-Based Nanoparticles as Antimicrobial Agents: An Overview, *Nanomaterials*, 10 (2), 292
55. El-Mageed, A., Taia, A., Shaaban, A., El-Mageed, A., Shima, A., Semida, W. M., et al. (2021). Silicon defensive role in maize (*Zea mays* L.) against drought stress and metals-contaminated irrigation water. *Silicon* 13 (7), 2165–2176. doi: 10.1007/s12633-020-00690-0
56. El-Sharkawy, M.S.; El-Beshbseshy, T.R.; Mahmoud, E.K.; Abdelkader, N.I.; Al-Shal, R.M.; Missaoui, A.M. Response of Alfalfa under Salt Stress to the Application of Potassium Sulfate Nanoparticles. *Am. J. Plant Sci.* 2017, 8, 1751–1773.
57. Elsheery, N.I.; Sunoj, V.; Wen, Y.; Zhu, J.; Muralidharan, G.; Cao, K. Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. *Plant Physiol. Biochem.* 2020, 149, 50–60.
58. El-Zohri, M., Al-Wadaani, N. A., Bafeel, S. O. (2021). Foliar sprayed green zinc oxide nanoparticles mitigate drought-induced oxidative stress in tomato. *Plants* 10, 2400. doi: 10.3390/plants10112400
59. El-Zohri, M.; Al-Wadaani, N.A.; Bafeel, S.O. Foliar Sprayed Green Zinc Oxide Nanoparticles Mitigate Drought-Induced Oxidative Stress in Tomato. *Plants* 2021, 10, 2400.

60. Emamverdian, A.; Ding, Y.; Mokhberdorran, F.; Xie, Y. Heavy Metal Stress and Some Mechanisms of Plant Defense Response. *Sci. World J.* 2015, 2015, 756120.
61. Emiliani, J., D'andrea, L., Lorena Falcone Ferreyra, M., Mauli3n, E., Rodriguez, E., Rodriguez-Concepci3n, M., et al. (2018). A role for β , β -xanthophylls in *Arabidopsis* UV-b photoprotection. *J. Exp. Bot.* 69, 4921–4933. doi: 10.1093/jxb/ery242
62. Faraji, J., Sepehri, A. (2020). Exogenous nitric oxide improves the protective effects of TiO₂ nanoparticles on growth, antioxidant system, and photosynthetic performance of wheat seedlings under drought stress. *J. Soil Sci. Plant Nutrit.* 20, 703–714. doi: 10.1007/s42729-019-00158-0
63. Farooq, M., Nawaz, A., Chaudhry, M., Indrasti, R., Rehman, A. (2017). Improving resistance against terminal drought in bread wheat by exogenous application of proline and gamma-aminobutyric acid. *J. Agron. Crop Sci.* 203, 464–472. doi: 10.1111/jac.12222
64. Farooq, M.; Hussain, M.; Wahid, A.; Siddique, K.H.M. Drought stress in plants: An overview. In *Plant Responses to Drought Stress*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 1–33.
65. Fathi, A., Tari, D. B. (2016). Effect of drought stress and its mechanism in plants. *Int. J. Life Sci.* 10, 1–6. doi: 10.3126/ijls.v10i1.14509
66. Fatollahpour Grangah, M., Rashidi, V., Mirshekari, B., Khalilvand Behrouzfar, E., Farahvash, F. (2020). Effects of nano-fertilizers on physiological and yield characteristics of pinto bean cultivars under water deficit stress. *J. Plant Nutrit.* 43, 2898–2910. doi: 10.1080/01904167.2020.1799000
67. Feng, P., Weicheng, C. (2016). Properties, application and synthesis methods of nano-molybdenum powder. *J. Mater. Sci. Chem. Eng.* 4, no. 09, 36. doi: 10.4236/msce.2016.49004
68. Feng, Y., Cui, X., He, S., Dong, G., Chen, M., Wang, J., et al. (2013). The role of metal nanoparticles in influencing arbuscular mycorrhizal fungi effects on plant growth. *Environ. Sci. Technol.* 47, 9496–9504. doi: 10.1021/es402109n
69. Ge, Y., Priester, J. H., Van De Werfhorst, L. C., Walker, S. L., Nisbet, R. M., An, Y.-J., et al. (2014). Soybean plants modify metal oxide nanoparticle effects on soil bacterial communities. *Environ. Sci. Tec.* 48, 13489–13496. doi: 10.1021/es5031646
70. Genc, Y., Taylor, J., Lyons, G., Li, Y., Cheong, J., Appelbee, M., et al. (2019). Bread wheat with high salinity and sodicity tolerance. *Front. Plant Sci.* 10, 1280. doi: 10.3389/fpls.2019.01280
71. Ghabel, V.K.; Karamian, R. Effects of TiO₂ nanoparticles and spermine on antioxidant responses of *Glycyrrhiza glabra* L. to cold stress. *Acta Bot. Croat.* 2020, 79, 137–147.
72. Ghaednia, H., Hossain, M. S., & Jackson, R. L. (2016). Tribological performance of silver nanoparticle-enhanced polyethylene glycol lubricants. *Tribology Transactions*, 59(4), 585-592.
73. Ghani, M. I., Saleem, S., Rather, S. A., Rehmani, M. S., Alamri, S., Rajput, V. D., et al. (2022). Foliar application of zinc oxide nanoparticles: An effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. *Chemosphere* 289, 133202. doi: 10.1016/j.chemosphere.2021.133202
74. Gohari, G., Mohammadi, A., Akbari, A., Panahirad, S., Dadpour, M. R., Fotopoulos, V., et al. (2020). Titanium dioxide nanoparticles (TiO₂ NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of *Dracocephalum moldavica*. *Sci. Rep.* 10, 1–14. doi: 10.1038/s41598-020-57794-1
75. Gottschalk, F., Sun, T., Nowack, B. (2013). Environmental concentrations of engineered nanomaterials: review of modeling and analytical studies. *Environ. pollut.* 181, 287–300. doi: 10.1016/j.envpol.2013.06.003
76. Hafeez, A., Razzaq, A., Mahmood, T., Jhazab, H. M. (2015). Potential of copper nanoparticles to increase growth and yield of wheat. *J. Nanosci. Adv. Technol.* 1, 6–11. doi: 10.24218/jnat.2015.02
77. Hafez, E. M., Osman, H. S., Gowayed, S. M., Okasha, S. A., Omara, A. E.-D., Sami, R., et al. (2021).

- Minimizing the adversely impacts of water deficit and soil salinity on maize growth and productivity in response to the application of plant growth-promoting rhizobacteria and silica nanoparticles. *Agronomy* 11, 676. doi: 10.3390/agronomy11040676
78. Hafez, Y., Attia, K., Alamery, S., Ghazy, A., Al-Doss, A., Ibrahim, E., et al. (2020). Beneficial effects of biochar and chitosan on antioxidative capacity, osmolytes accumulation, and anatomical characters of water-stressed barley plants. *Agronomy* 10, 630. doi: 10.3390/agronomy10050630
79. Haider, A., Al-Anbari, R., Kadhim, G., & Jameel, Z. (2018). Synthesis and photocatalytic activity for TiO₂ nanoparticles as air purification. In MATEC Web of Conferences (Vol. 162, p. 05006).
80. Handy, R. D., Shaw, B. J. (2007). Toxic effects of nanoparticles and nanomaterials: implications for public health, risk assessment and the public perception of nanotechnology. *Health Risk Soc* 9 (2), 125–144. doi: 10.1080/13698570701306807
81. Hasan, M. M., Gong, L., Nie, Z.-F., Li, F.-P., Ahammed, G. J., Fang, X.-W. (2021a). ABA-induced stomatal movements in vascular plants during dehydration and rehydration. *Environ. Exp. Bot.* 186, 104436. doi: 10.1016/j.envexpbot.2021.104436
82. Hasan, M. M., Skalicky, M., Jahan, M. S., Hossain, M. N., Anwar, Z., Nie, Z.-F., et al. (2021b). Spermine: its emerging role in regulating drought stress responses in plants. *Cells* 10, 261. doi: 10.3390/cells10020261
83. Hasanpour, H.; Maali-Amir, R.; Zeinali, H. Effect of TiO₂ nanoparticles on metabolic limitations to photosynthesis under cold in chickpea. *Russ. J. Plant Physiol.* 2015, 62, 779–787.
84. Hashem, A. H., Abdelaziz, A. M., Askar, A. A., Fouda, H. M., Khalil, A. M., Abd-Elsalam, K. A., et al. (2021). *Bacillus megaterium*-mediated synthesis of selenium nanoparticles and their antifungal activity against *Rhizoctonia solani* in faba bean plants. *J. Fungi* 7, 195. doi: 10.3390/jof7030195
85. Hassan, M., U., Aamer, M., Umer, C. M., Haiying, T., Shahzad, B., Barbanti, L., et al. (2020). The critical role of zinc in plants facing the drought stress. *Agriculture* 10, 396. doi: 10.3390/agriculture10090396
86. Hassan, N.S.; El Din, T.A.S.; Hendawey, M.H.; Borai, I.H.; Mahdi, A.A. Magnetite and zinc oxide nanoparticles alleviated heat stress in wheat plants. *Curr. Nanomater.* 2018, 3, 32–43.
87. Hatami, M., Ghorbanpour, M. (2014). Defense enzyme activities and biochemical variations of pelargonium zonale in response to nanosilver application and dark storage. *Turk. J. Biol.* 38, 130–139. doi: 10.3906/biy-1304-64
88. Havas, F., Ghaderi, N. (2018). Application of iron nanoparticles and salicylic acid in *in vitro* culture of strawberries (*Fragaria x ananassa* Duch.) to cope with drought stress. *Plant Cell. Tiss. Organ Cul. (PCTOC)*. 132, 511–523. doi: 10.1007/s11240-017-1347-8
89. Heikal, Y. M., El-Esawi, M. A., El-Ballat, E. M., Abdel-Aziz, H. M. (2022). Applications of nanoparticles for mitigating salinity and drought stress in plants: an overview on the physiological, biochemical, and molecular genetic aspects. *New Z. J. Crop Hortic. Sci.*, 1–31. doi: 10.1080/01140671.2021.2016870
90. Hernandez-Viezcas, J., Castillo-Michel, H., Servin, A., Peralta-Videa, J., Gardea-Torresdey, J. (2011). Spectroscopic verification of zinc absorption and distribution in the desert plant *Prosopis juliflora*-velutina (*velvet mesquite*) treated with ZnO nanoparticles. *Chem. Engin.* 170, 346–352. doi: 10.1016/j.cej.2010.12.021
91. Herrera-Becerra, R., Rius, J., Zorrilla, C. (2010). Tannin biosynthesis of iron oxide nanoparticles. *App. Phy. A* 100, 453–459. doi: 10.1007/s00339-010-5903-x
92. Hoekstra, F. A., Golovina, E. A., Buitink, J. (2001). Mechanisms of plant desiccation tolerance. *Trends Plant Sci.* 6, 431–438. doi: 10.1016/S1360-1385(01)02052-0
93. Hou, J., Wu, Y., Li, X., Wei, B., Li, S., Wang, X. (2018). Toxic effects of different types of zinc oxide nanoparticles on algae, plants, invertebrates,

- vertebrates, and microorganisms. *Chemosphere* 193, 852–860. doi: 10.1016/j.chemosphere.2017.11.077
94. Hsin, Y. H., Chen, C. F., Huang, S., Shih, T. S., Lai, P. S., Chueh, P. J. (2008). The apoptotic effect of nanosilver is mediated by a ROS-and JNK-dependent mechanism involving the mitochondrial pathway in NIH3T3 cells. *Toxicol. Lett.* 179 (3), 130–139. doi: 10.1016/j.toxlet.2008.04.015
95. Hu, S.; Ding, Y.; Zhu, C. Sensitivity and responses of chloroplasts to heat stress in plants. *Front. Plant Sci.* 2020, 11, 375.
96. Ibrahim, I. D., Jamiru, T., Sadiku, E. R., Hamam, Y., Alayli, Y., & Eze, A. A. (2019). Application of nanoparticles and composite materials for energy generation and storage. *IET Nanodielectrics*, 2(4), 115-122.
97. Iqbal, M.; Raja, N.I.; Mashwani, Z.-U.; Hussain, M.; Ejaz, M.; Yasmeen, F. Effect of silver nanoparticles on growth of wheat Under Heat Stress. *Iran. J. Sci. Technol. Trans. A Sci.* 2019, 43, 387–395.
98. Isayenkov, S.V.; Maathuis, F.J.M. Plant Salinity Stress: Many Unanswered Questions Remain. *Front. Plant Sci.* 2019, 10, 80.
99. Itrotwar, P. D., Govindaraju, K., Tamilselvan, S., Kannan, M., Raja, K., Subramanian, K. S. (2020). Seaweed-based biogenic ZnO nanoparticles for improving agro-morphological characteristics of rice (*Oryza sativa* L.). *J. Plant Grow. Reg.* 39, 717–728. doi: 10.1007/s00344-019-10012-3
100. Jaberzadeh, A., Moaveni, P., Moghadam, H. R. T., Zahedi, H. (2013). 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. Agrobo. Cluj-Nap.* 41, 201–207. doi: 10.15835/nbha4119093
101. Jacobasch, C., Völker, C., Giebner, S., Völker, J., Alsenz, H., Potouridis, T., et al. (2014). Long-term effects of nanoscaled titanium dioxide on the cladoceran *Daphnia magna* over six generations. *Environ. pollut.* 186, pp.180–pp.186. doi: 10.1016/j.envpol.2013.12.008
102. Jain, S., Hirst, D. G., & O'Sullivan, J. (2012). Gold nanoparticles as novel agents for cancer therapy. *The British Journal of Radiology*, 85(1010), 101-113.
103. Javed, R., Usman, M., Yücesan, B., Zia, M., Gürel, E. (2017). Effect of zinc oxide (ZnO) nanoparticles on physiology and steviol glycosides production in micro propagated shoots of stevia rebaudiana bertonii. *Plant Physiol. Biochem.* 110, 94–99. doi: 10.1016/j.plaphy.2016.05.032
104. Javed, R., Zia, M., Naz, S. (2020). Role of capping agents in the application of nanoparticles in biomedicine and environmental remediation: recent trends and future prospects. *J. Nanobiotech* 18, 172. doi: 10.1186/s12951-020-00704-4
105. Kandhol, N., Jain, M., Tripathi, D. K. (2022). Nanoparticles as potential hallmarks of drought stress tolerance in plants. *Physiol. Plant.* 174 (2), e13665. doi: 10.1111/pp1.13665
106. Kandhol, N.; Jain, M.; Tripathi, D.K. Nanoparticles as potential hallmarks of drought stress tolerance in plants. *Physiol. Plant.* 2022, 174, e13665.
107. Kardavan Ghabel, V., Karamian, R. (2020). The effects of titanium dioxide nanoparticles and spermine on physiological responses of licorice (*Glycyrrhiza glabra* L.) to cold stress. *J. Plant Physiol. Breed.* 10, 93–110.
108. Khalisanni K., Xuefei T., Hayyiratul F. M. Z., Yang T., Chien L. C., Dinh-Toi C., Man, Kee L., Yeek C. H., Jun W. L., & Lai C. W., (2020). Advanced in developmental organic and inorganic nanomaterial: a review, *Bioengineered*, 11, 1, 328-355
109. Khan, F. A. (2020). Synthesis of Nanomaterials: Methods & Technology. In *Applications of Nanomaterials in Human Health* (pp. 15-21). Springer, Singapore. Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, 12(7), 908-931

110. Khan, I., Saeed, K., Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arab. J. Chemi.* 12, 908–931. doi: 10.1016/j.arabjc.2017.05.011
111. Khan, I.; Raza, M.A.; Awan, S.A.; Shah, G.A.; Rizwan, M.; Ali, B.; Tariq, R.; Hassan, M.J.; Alyemeni, M.N.; Brestic, M.; et al. Amelioration of salt induced toxicity in pearl millet by seed priming with silver nanoparticles (AgNPs): The oxidative damage, antioxidant enzymes and ions uptake are major determinants of salt tolerant capacity. *Plant Physiol. Biochem.* 2020, 156, 221–232.
112. Khan, M. N., Alsolami, M. A., Basahi, R. A., Siddiqui, M. H., Al-Huqail, A. A., Abbas, Z. K., et al. (2020). Nitric oxide is involved in nano-titanium dioxide-induced activation of antioxidant defense system and accumulation of osmolytes under water-deficit stress in *Vicia faba* l. *Ecotoxicol. Environ. Saf.* 190, 110152. doi: 10.1016/j.ecoenv.2019.110152
113. Khan, M. N., Mobin, M., Abbas, Z. K., Almutairi, K. A., Siddiqui, Z. H. (2017). Role of nanomaterials in plants under challenging environments. *Plant Physiol. Biochem.* 110, 194–209. doi: 10.1016/j.plaphy.2016.05.038
114. Khan, M., Khan, M. S. A., Borah, K. K., Goswami, Y., Hakeem, K. R., Chakrabartty, I. (2021). The potential exposure and hazards of metal-based nanoparticles on plants and environment, with special emphasis on ZnO NPs, TiO₂ NPs, and AgNPs: A review. *Environ. Adv.* 6, 100128. doi: 10.1016/j.envadv.2021.100128
115. Khan, M., Naqvi, A. H., Ahmad, M. (2015). Comparative study of the cytotoxic and genotoxic potentials of zinc oxide and titanium dioxide nanoparticles. *Toxicol. Rep.* 2, pp.765–pp.774. doi: 10.1016/j.toxrep.2015.02.004
116. Khanra, S., Abdullah-Al Mamun, M., Ferreira, F. F., Ghosh, K., Guha, S. (2018). Functionalized self-assembled peptide nanotubes with cobalt ferrite nanoparticles for applications in organic electronics. *ACS App. Nano. Mat.* 1, 1175–1187. doi: 10.1021/acsanm.7b00344
117. Kim, Y.-H.; Khan, A.L.; Waqas, M.; Lee, I.-J. Silicon Regulates Antioxidant Activities of Crop Plants under Abiotic-Induced Oxidative Stress: A Review. *Front. Plant Sci.* 2017, 8, 510.
118. Kopittke, P. M., Lombi, E., Wang, P., Schjoerring, J. K., Husted, S. (2019). Nanomaterials as fertilizers for improving plant mineral nutrition and environmental outcomes. *Environ. Sci.: Nano.* 6, 3513–3524. doi: 10.1039/C9EN00971J
119. Kumari, M., Khan, S. S., Pakrashi, S., Mukherjee, A., Chandrasekaran, N. (2011). Cytogenetic and genotoxic effects of zinc oxide nanoparticles on root cells of allium cepa. *J. Haz. Mat.* 190, 613–621. doi: 10.1016/j.jhazmat.2011.03.095
120. Larue, C., Castillo-Michel, H., Sobanska, S., Cécillon, L., Bureau, S., Barthès, V., et al. (2014). Foliar exposure of the crop *Lactuca sativa* to silver nanoparticles: evidence for internalization and changes in Ag speciation. *J. Haz. Mat.* 264, 98–106. doi: 10.1016/j.jhazmat.2013.10.053
121. Li, M., Zhang, P., Adeel, M., Guo, Z., Chetwynd, A. J., Ma, C., et al. (2021). Physiological impacts of zero valent iron, Fe₃O₄ and Fe₂O₃ nanoparticles in rice plants and their potential as Fe fertilizers. *Environ. pollut.* 269, 116134. doi: 10.1016/j.envpol.2020.116134
122. Linh, T. M., Mai, N. C., Hoe, P. T., Lien, L. Q., Ban, N. K., Hien, L. T. T., et al. (2020). Metal-based nanoparticles enhance drought tolerance in soybean. *J. Nanomat.* 2020, 4056563. doi: 10.1155/2020/4056563
123. Mafakheri, A., Siosemardeh, A., Bahramnejad, B., Struik, P., Sohrabi, Y. (2010). Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. *Aust. J. Crop Sci.* 4, 580–585.
124. Mahdy, A. M., Sherif, F. K., Elkhatib, E. A., Fathi, N. O., Ahmed, M. H. (2020). Seed priming in nanoparticles of water treatment residual can increase the germination and growth of cucumber seedling under salinity stress. *J. Plant Nutrit.* 43, 1862–1874. doi: 10.1080/01904167.2020.1750647
125. Mahmood, R.; Ijaz, M.; Qamar, S.; Bukhari, S.A.; Malik, K. Abiotic stress signaling in rice crop. In *Advances in Rice Research for Abiotic Stress*

- Tolerance; Mirza, H., Masayuku, F., Kamrun, N., Jiban, B., Eds.; Woodhead Publishing: Sawston, UK, 2019; pp. 551–569.
126. Maity, A., Natarajan, N., Vijay, D., Srinivasan, R., Pastor, M., Malaviya, D. R. (2018). Influence of metal nanoparticles (NPs) on germination and yield of oat (*Avena sativa*) and berseem (*Trifolium alexandrinum*). *Pro. Nat. Acad. Sci. India. Sect. B.: Biol. Sci.* 88, 595–607. doi: 10.1007/s40011-016-0796-x
127. Majumdar, S., Almeida, I. C., Arigi, E. A., Choi, H., Verberkmoes, N. C., Trujillo-Reyes, J., et al. (2015). Environmental effects of nanoceria on seed production of common bean (*Phaseolus vulgaris*): a proteomic analysis. *Environ. Sci. Tech.* 49, 13283–13293. doi: 10.1021/acs.est.5b03452
128. Mangena, P. (2018). “Water stress: morphological and anatomical changes in soybean (*Glycine max* l.) plants,” in *Plant, abiotic stress and resp. climate change*, 9–31. doi: 10.5772/intechopen.72899
129. Matuszak-Slamani, R., Bejger, R., Włodarczyk, M., Kulpa, D., Sienkiewicz, M., Gołębiowska, D., et al. (2022). Effect of humic acids on soybean seedling growth under polyethylene-glycol-6000-induced drought stress. *Agronomy* 12, 1109. doi: 10.3390/agronomy12051109
130. McKenzie, B. M., Mullins, C. E., Tisdall, J. M., Bengough, A. G. (2013). Root–soil friction: quantification provides evidence for measurable benefits for manipulation of root-tip traits. *Plant. Cell Environ.* 36, 1085–1092. doi: 10.1111/pce.12037
131. Miller, N. J., Rice-Evans, C. A. (1997). Factors influencing the antioxidant activity determined by the ABTS•+ radical cation assay. *Free Rad. Res.* 26, 195–199. doi: 10.3109/10715769709097799
132. Mittal, D., Kaur, G., Singh, P., Yadav, K., Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Front. Nanotech.* 2, 10. doi: 10.3389/fnano.2020.579954
133. Mohamad, A. T., Kaur, J., Sidik, N. A. C., & Rahman, S. (2018). Nanoparticles: A review on their synthesis, characterization and physicochemical properties for energy technology industry. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 46(1), 1-10.
134. Mohamed, A. K. S., Qayyum, M. F., Abdel-Hadi, A. M., Rehman, R. A., Ali, S., Rizwan, M. (2017). Interactive effect of salinity and silver nanoparticles on photosynthetic and biochemical parameters of wheat. *Arch. Agron. Soil Sci.* 63, 1736–1747. doi: 10.1080/03650340.2017.1300256
135. Mohamed, H.I.; Sajyan, T.K.; Shaalan, R.; Bejjani, R.; Sassine, Y.N.; Basit, A. Plant-mediated copper nanoparticles for agri-ecosystem applications. In *Agri-Waste and Microbes for Production of Sustainable Nanomaterials*; Kamel, A.A., Rajiv, P., Rajeshkumar, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 79–120.
136. Mohammadi, H., Esmailpour, M., Gheranpaye, A. (2016). Effects of TiO₂ nanoparticles and water-deficit stress on morpho-physiological characteristics of dragonhead (*Dracocephalum moldavica* l.) plants. *Acta Agricul. Slo.* 107, 385–396. doi: 10.14720/aas.2016.107.2.11
137. Mohammadi, R.; Maali-Amiri, R.; Abbasi, A. Effect of TiO₂ Nanoparticles on Chickpea Response to Cold Stress. *Biol. Trace Elem. Res.* 2013, 152, 403–410.
138. Mohammadi, R.; Maali-Amiri, R.; Mantri, N. Effect of TiO₂ nanoparticles on oxidative damage and antioxidant defense systems in chickpea seedlings during cold stress. *Russ. J. Plant Physiol.* 2014, 61, 768–775.
139. Morales, F., Ancín, M., Fakhret, D., González-Torralba, J., Gámez, A. L., Seminario, A., et al. (2020). Photosynthetic metabolism under stressful growth conditions as a bases for crop breeding and yield improvement. *Plants* 9, 88. doi: 10.3390/plants9010088
140. Mustafa, G.; Komatsu, S. Insights into the response of soybean mitochondrial proteins to various sizes of aluminum oxide nanoparticles under flooding stress. *J. Proteome Res.* 2016, 15, 4464–4475.

141. Mustafa, G.; Sakata, K.; Komatsu, S. Proteomic analysis of flooded soybean root exposed to aluminum oxide nanoparticles. *J. Proteom.* 2015, 128, 280–297.
142. Mustafa, G.; Sakata, K.; Komatsu, S. Proteomic analysis of soybean root exposed to varying sizes of silver nanoparticles under flooding stress. *J. Proteom.* 2016, 148, 113–125.
143. Mustafa, H., Ilyas, N., Akhtar, N., Raja, N. I., Zainab, T., Shah, T., et al. (2021). 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.* 223, 112519. doi: 10.1016/j.ecoenv.2021.112519
144. Nel, A., Xia, T., Madler, L., Li, N. (2006). Toxic potential of materials at the nanolevel. *Science* 311 (5761), 622–627. doi: 10.1126/science.111439
145. Ozturk, M.; Unal, B.T.; García-Caparrós, P.; Khursheed, A.; Gul, A.; Hasanuzzaman, M. Osmoregulation and its actions during the drought stress in plants. *Physiol. Plant.* 2020, 172, 1321–1335.
146. Pal, S., Mondal, S., Pal, P., Das, A., & Maity, J. (2021). Fabrication of AgNPs/Silane coated mechanical and washing durable hydrophobic cotton textile for self-cleaning and oil water separation application. *Journal of the Indian Chemical Society*, 100283.
147. Pandey, G., Jain, P. (2020). Assessing the nanotechnology on the grounds of costs, benefits, and risks. *beni-suef uni. J. Basic. App. Sci.* 9 (1), pp.1–pp10. doi: 10.1186/s43088-020-00085-5
148. Paramo, L. A., Feregrino-Pérez, A. A., Guevara, R., Mendoza, S., Esquivel, K. (2020). Nanoparticles in agroindustry: applications, toxicity, challenges, and trends. *Nanomaterials* 10, 1654. doi: 10.3390/nano10091654
149. Patel K. P., Singh R. K., Kim, H. W., (2019). Carbon-based nanomaterials as an emerging platform for theranostics, *Mater. Horiz.*, 6, 434-469
150. Patra, J. K., Baek, K. H. (2014). Green nanobiotechnology: factors affecting synthesis and characterization techniques. *J. Nanomat.* 2014, 417305. doi: 10.1155/2014/417305
151. Peng, Y., Yu, Z., Pan, Y., & Zeng, G. (2018). Antibacterial photocatalytic self-cleaning poly (vinylidene fluoride) membrane for dye wastewater treatment. *Polymers for Advanced Technologies*, 29(1), 254-262.
152. Pérez-Labrada, F., Hernández-Hernández, H., López-Pérez, M. C., González-Morales, S., Benavides-Mendoza, A., Juárez-Maldonado, A. (2020). “Nanoparticles in plants: morphophysiological, biochemical, and molecular responses,” in *Plant life under changing environ* (Elsevier), 289–322. doi: 10.1016/B978-0-12-818204-8.00016-3
153. Petrov, P., Petrova, A., Dimitrov, I., Tashev, T., Olsovská, K., Brestic, M., et al. (2018). Relationships between leaf morpho-anatomy, water status and cell membrane stability in leaves of wheat seedlings subjected to severe soil drought. *J. Agron. Crop Sci.* 204, 219–227. doi: 10.1111/jac.12255
154. Posmyk, M., Kontek, R., Janas, K. (2009). Antioxidant enzymes activity and phenolic compounds content in red cabbage seedlings exposed to copper stress. *Ecotoxicol. Environ. Saf.* 72, 596–602. doi: 10.1016/j.ecoenv.2008.04.024
155. Potter, M.; Deakin, J.; Cartwright, A.; Hortin, J.; Sparks, D.; Anderson, A.J.; McLean, J.E.; Jacobson, A.; Britt, D.W. Absence of Nanoparticle-Induced Drought Tolerance in Nutrient Sufficient Wheat Seedlings. *Environ. Sci. Technol.* 2021, 55, 13541–13550.
156. Rahmatpour, S., Mosaddeghi, M. R., Shirvani, M., Šimůnek, J. (2018). Transport of silver nanoparticles in intact columns of calcareous soils: The role of flow conditions and soil texture. *Geoderma* 322, 89–100. doi: 10.1016/j.geoderma.2018.02.016
157. Rajput, V. D., Minkina, T. M., Behal, A., Sushkova, S. N., Mandzhieva, S., Singh, R., et al. (2018). Effects of zinc-oxide nanoparticles on soil, plants, animals and soil organisms: A review. *Environ. Nanotech. Monit.*

- Manage. 9, 76–84. doi: 10.1016/j.enmm.2017.12.006
158. Raliya, R., Franke, C., Chavalmane, S., Nair, R., Reed, N., Biswas, P. (2016). Quantitative understanding of nanoparticle uptake in watermelon plants. *Front. Plant Sci.* 7, 1288. doi: 10.3389/fpls.2016.01288
159. Rane, A. V., Kanny, K., Abitha, V. K., & Thomas, S. (2018). Methods for synthesis of nanoparticles and fabrication of nanocomposites. In *Synthesis of Inorganic Nanomaterials* (pp. 121-139). Woodhead Publishing.
160. Rao, D. E., Chaitanya, K. V. (2019). Morphological and physiological responses of seven different soybean (*Glycine max* L. merr.) cultivars to drought stress. *J. Crop Sci. Biotech.* 22, 355–362. doi: 10.1007/s12892-019-0088-0
161. Rasheed A, Li H, Tahir MM, Mahmood A, Nawaz M, Shah AN, Aslam MT, Negm S, Moustafa M, Hassan MU and Wu Z (2022) The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. *Front. Plant Sci.* 13:976179. doi: 10.3389/fpls.2022.976179
162. Rasheed, A., Jie, Y., Nawaz, M., Hongdong, J., Yushen, M., Hassan, M. U., et al. (2022a). Improving drought stress tolerance in ramie (*Boehmeria nivea* L.) by using molecular techniques. *Front. Plant Sci.* 13, 911610. doi: 10.3389/fpls.2022.911610
163. Rasheed, A., Mahmood, A., Maqbool, R., Albaqami, M., Sher, A., Sattar, A., et al. (2022b). Key insights to develop drought-resilient soybean: A review. *J. King. Saud. Uni-Sci.* 102089. doi: 10.1016/j.jksus.2022.102089
164. Rodrigues, S. M., Demokritou, P., Dokoozlian, N., Hendren, C. O., Karn, B., Mauter, M. S., et al. (2017). Nanotechnology for sustainable food production: promising opportunities and scientific challenges. *Environ. Sci.: Nano.* 4, 767–781. doi: 10.1039/C6EN00573J
165. Rossi, L.; Zhang, W.; Ma, X. Cerium oxide nanoparticles alter the salt stress tolerance of *Brassica napus* L. by modifying the formation of root apoplastic barriers. *Environ. Pollut.* 2017, 229, 132–138.
166. Rubilar, O., Rai, M., Tortella, G., Diez, M. C., Seabra, A. B., Durán, N. (2013). Biogenic nanoparticles: copper, copper oxides, copper sulphides, complex copper nanostructures and their applications. *Biotech. Lett.* 35, 1365–1375. doi: 10.1007/s10529-013-1239-x
167. Rushton, P. J., Somssich, I. E., Ringler, P., Shen, Q. J. (2010). WRKY transcription factors. *Trends Plant Sci.* 15, 247–258. doi: 10.1016/j.tplants.2010.02.006
168. Sathyanarayanan, M. B., Balachandranath, R., Genji Srinivasulu, Y., Kannaiyan, S. K., & Subbiahdoss, G. (2013). The effect of gold and iron-oxide nanoparticles on biofilm-forming pathogens. *ISRN Microbiol.* 2013:272086.
169. Savita Kumari and Leena Sarkar, 2021. A Review on Nanoparticles: Structure, Classification, Synthesis & Applications. *Journal of Scientific Research*, Volume 65, Issue 8, 2021
170. Schaller, J., Brackhage, C., Paasch, S., Brunner, E., Bäucker, E., Dudel, E. G. (2013). Silica uptake from nanoparticles and silica condensation state in different tissues of *Phragmites australis*. *Sc. Total. Environ.* 442, 6–9. doi: 10.1016/j.scitotenv.2012.10.016
171. Schittenhelm, S. (2010). Effect of drought stress on yield and quality of maize/sunflower and maize/sorghum intercrops for biogas production. *J. Agro. Crop Sci.* 196, 253–261. doi: 10.1111/j.1439-037X.2010.00418.x
172. Schwab, F., Zhai, G., Kern, M., Turner, A., Schnoor, J. L., Wiesner, M. R. (2016). Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants—critical review. *Nanotoxicology* 10, 257–278. doi: 10.3109/17435390.2015.1048326
173. Seabra, A. B., Durán, N. (2015). Nanotoxicology of metal oxide nanoparticles. *Metals* 5, 934–975. doi: 10.3390/met5020934

174. Seabra, A. B., PasquôTo, T., Ferrarini, A. C. F., Santos, M. D. C., Haddad, P. S., De Lima, R. (2014). Preparation, characterization, cytotoxicity, and genotoxicity evaluations of thiolated-and s-nitrosated superparamagnetic iron oxide nanoparticles: implications for cancer treatment. *Chem. Res. Toxicol.* 27, 1207–1218. doi: 10.1021/tx500113u
175. Seleiman, M. F., Al-Suhaibani, N., Ali, N., Akmal, M., Alotaibi, M., Refay, Y., et al. (2021). Drought stress impacts on plants and different approaches to alleviate its adverse effects. *Plants* 10, 259. doi: 10.3390/plants10020259
176. Selvakumari, D., Deepa, R., Mahalakshmi, V., Subhashini, P., Lakshminarayan, N. (2015). Anti-cancer activity of ZnO nanoparticles on MCF7 (breast cancer cell) and A549 (lung cancer cell). *ARPN. J. Eng. Appl. Sci.* 10, 5418–5421.
177. Semida, W. M., Abdelkhalik, A., Mohamed, G. F., Abd El-Mageed, T. A., Abd El-Mageed, S. A., Rady, M. M., et al. (2021). Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena* l.). *Plants* 10, 421. doi: 10.3390/plants10020421
178. Senthil, M., Ramesh, C. (2012). Biogenic synthesis of Fe₃O₄ nanoparticles using tridax procumbens leaf extract and its antibacterial activity on *Pseudomonas aeruginosa*. *Dig. J. Nanomat. Biostruct. (DJNB)*. 7, 1655–1660.
179. Shafea, A. A., Dawood, M. F., Zidan, M. A. (2017). Wheat seedlings traits as affected by soaking at titanium dioxide nanoparticles. *Enviro. Earth Ecol.* 1, 102–111. doi: 10.24051/eee/68607
180. Shah, S. M. D. M., Shabbir, G., Malik, S. I., Raja, N. I., Shah, Z. H., Rauf, M., et al. (2022). Delineation of physiological, agronomic and genetic responses of different wheat genotypes under drought condition. *Agronomy* 12, 1056. doi: 10.3390/agronomy12051056
181. Shah, Z. H., Rehman, H. M., Akhtar, T., Daur, I., Nawaz, M. A., Ahmad, M. Q., et al. (2017). Redox and ionic homeostasis regulations against oxidative, salinity and drought stress in wheat (a systems biology approach). *Front. Genet.* 8, 141. doi: 10.3389/fgene.2017.00141
182. Sharif, F., Westerhoff, P., Herckes, P. (2013). Sorption of trace organics and engineered nanomaterials onto wetland plant material. *Environ. Sci.: Proc. Impacts.* 15, 267–274. doi: 10.1039/C2EM30613A
183. Shin W. K., Cho J., Kannan A. G., Lee Y. S. & Kim W., (2016). Cross- linked composite gel polymer electrolyte using mesoporous methacrylate functionalized SiO₂ nanoparticles for lithium- ion polymer batteries, *Science Report*, 6, 26332
184. Shoarian, N., Jamei, R., Pasban Eslam, B., Salehi Lisar, S. Y. (2020). Titanium dioxide nanoparticles increase resistance of *I. iberica* to drought stress due to increased accumulation of protective antioxidants. *Iran. J. Plant Physiol.* 10, 3343–3354.
185. Sierla, M., Waszczak, C., Vahisalu, T., Kangasjärvi, J. (2016). Reactive oxygen species in the regulation of stomatal movements. *Plant Physiol.* 171, 1569–1580. doi: 10.1104/pp.16.00328
186. Silva, S., Dias, M. C., Silva, A. (2022). Titanium and zinc-based nanomaterials in agriculture: A promising approach to deal with (A) biotic stresses? *Toxics* 10, 172. doi: 10.3390/toxics10040172
187. Singh, P., Kim, Y.-J., Zhang, D., Yang, D.-C. (2016). Biological synthesis of nanoparticles from plants and microorganisms. *Trends Biotech.* 34, 588–599. doi: 10.1016/j.tibtech.2016.02.006
188. Sinha, R.K.; Verma, S.S. Proteomics approach in horticultural crops for abiotic-stress tolerance. In *Stress Tolerance in Horticultural Crops*; Woodhead Publishing: Sawston, UK, 2021; pp. 371–385.
189. Song, Y.; Jiang, M.; Zhang, H.; Li, R. Zinc Oxide Nanoparticles Alleviate Chilling Stress in Rice (*Oryza Sativa* L.) by Regulating Antioxidative System and Chilling Response Transcription Factors. *Molecules* 2021, 26, 2196.
190. Sreevani, K., Anierudhe, V. V. (2022). Synthesis and characterization of molybdenum oxide nanoparticles by green method useful in antifungal applications against *colletotrichum gloeosporioides*. *J. Biomat.*

- Tissue Engin.* 12 (6), 1071–1079. doi: 10.1166/jbt.2022.3021
191. Sun, L., Song, F., Guo, J., Zhu, X., Liu, S., Liu, F., et al. (2020). Nano-ZnO-induced drought tolerance is associated with melatonin synthesis and metabolism in maize. *Int. J. Mol. Sci.* 21, 782. doi: 10.3390/ijms21030782
192. Sun, L., Song, F., Zhu, X., Liu, S., Liu, F., Wang, Y., et al. (2021). Nano-ZnO alleviates drought stress via modulating the plant water use and carbohydrate metabolism in maize. *Arch. Agro. Soil Sc.* 67, 245–259. doi: 10.1080/03650340.2020.1723003
193. Sutulienė, R., Ragelienė, L., Samuolienė, G., Brazaitytė, A., Urbutis, M., Miliauskienė, J. (2021). The response of antioxidant system of drought-stressed green pea (*Pisum sativum* L.) affected by watering and foliar spray with silica nanoparticles. *Horticulturae* 8, 35. doi: 10.3390/horticulturae8010035
194. Suzuki, N., Miller, G., Salazar, C., Mondal, H. A., Shulaev, E., Cortes, D. F., et al. (2013). Temporal-spatial interaction between reactive oxygen species and abscisic acid regulates rapid systemic acclimation in plants. *Plant Cell* 25, 3553–3569. doi: 10.1105/tpc.113.114595
195. Sztandera, K., Gorzkiewicz, M., & Klajnert-Maculewicz, B. (2018). Gold nanoparticles in cancer treatment. *Molecular Pharmaceutics*, 16(1), 1-23.
196. Tiwari J. N., Tiwari R. N., Kim K. S., (2012). Zerodimensional, one-dimensional, two-dimensional and three-dimensional nanostructured materials for advanced electrochemical energy devices, *Progress in Materials Science*, 57, 724- 803
197. Tiwari, S.; Lata, C. Heavy Metal Stress, Signaling, and Tolerance Due to Plant-Associated Microbes: An Overview. *Front. Plant Sci.* 2018, 9, 452.
198. Tolaymat, T., El Badawy, A., Genaidy, A., Abdelraheem, W., Sequeira, R. (2017). Analysis of metallic and metal oxide nanomaterial environmental emissions. *J. Clean. Prod.* 143, 401–412. doi: 10.1016/j.jclepro.2016.12.094
199. Tripathi, D. K., Singh, S., Singh, S., Pandey, R., Singh, V. P., Sharma, N. C., et al. (2017a). An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. *Plant Physiol. Biochem.* 110, 2–12. doi: 10.1016/j.plaphy.2016.07.030
200. Tripathi, D. K., Singh, S., Singh, V. P., Prasad, S. M., Dubey, N. K., Chauhan, D. K. (2017b). Silicon nanoparticles more effectively alleviated UV-b stress than silicon in wheat (*Triticum aestivum*) seedlings. *Plant Physiol. Biochem.* 110, 70–81. doi: 10.1016/j.plaphy.2016.06.026
201. Vakilian, K. A. (2019). Gold nanoparticles-based biosensor can detect drought stress in tomato by ultrasensitive and specific determination of miRNAs. *Plant Physiol. Biochem.* 145, 195–204. doi: 10.1016/j.plaphy.2019.10.042
202. Van Nguyen, D., Nguyen, H. M., Le, N. T., Nguyen, K. H., Nguyen, H. T., Le, H. M., et al. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *J. Plant Growth Reg.* 41, 364–375. doi: 10.1007/s00344-021-10301-w
203. Venkatachalam, P., Priyanka, N., Manikandan, K., Ganeshbabu, I., Indiraarulsevi, P., Geetha, N., et al. (2017). Enhanced plant growth promoting role of phycocyanin coated zinc oxide nanoparticles with p supplementation in cotton (*Gossypium hirsutum* L.). *Plant Physiol. Biochem.* 110, 118–127. doi: 10.1016/j.plaphy.2016.09.004
204. Venkateswarlu, S., Rao, Y. S., Balaji, T., Prathima, B., Jyothi, N. (2013). Biogenic synthesis of Fe₃O₄ magnetic nanoparticles using plantain peel extract. *Mat. Lett.* 100, 241–244. doi: 10.1016/j.matlet.2013.03.018
205. Veziroglu, S., Hwang, J., Drewes, J., Barg, I., Shondo, J., Strunskus, T., & Aktas, O. C. (2020). PdO nanoparticles decorated TiO₂ film with enhanced photocatalytic and selfcleaning properties. *Materials Today Chemistry*, 16, 100251.
206. Wang, A.; Li, J.; 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, 2670.
207. Wang, K.; Wang, Y.; Wan, Y.; Mi, Z.; Wang, Q.; Wang, Q.; Li, H. The fate of arsenic in rice plants (*Oryza sativa* L.): Influence of different forms of selenium. *Chemosphere* 2021, 264, 128417.
208. Wang, W.-N., Tarafdar, J. C., Biswas, P. (2013). Nanoparticle synthesis and delivery by an aerosol route for watermelon plant foliar uptake. *J. Nanopart. Res.* 15, 1–13. doi: 10.1007/s11051-013-1417-8
209. Wang, X., Li, Q., Pei, Z., Wang, S. (2018). Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. *Biol. Plant* 62, 801–808. doi: 10.1007/s10535-018-0813-4
210. Wang, Y.; Liu, Y.; Zhan, W.; Zheng, K.; Lian, M.; Zhang, C.; Ruan, X.; Li, T. Long-term stabilization of Cd in agricultural soil using mercapto-functionalized nano-silica (MPTS/nano-silica): A three-year field study. *Ecotoxicol. Environ. Saf.* 2020, 197, 110600.
211. Wu, H.; Tito, N.; Giraldo, J.P. Anionic Cerium Oxide Nanoparticles Protect Plant Photosynthesis from Abiotic Stress by Scavenging Reactive Oxygen Species. *ACS Nano* 2017, 11, 11283–11297.
212. Xie, X., He, Z., Chen, N., Tang, Z., Wang, Q., Cai, Y. (2019). The roles of environmental factors in regulation of oxidative stress in plant. *BioMed. Res. Int.* 2019, 1–11. doi: 10.1155/2019/9732325
213. Yadav, S.K. Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. *S. Afr. J. Bot.* 2010, 76, 167–179.
214. Yalda Raeesi Sadati, S., Jahanbakhsh Godehkahriz, S., Ebadi, A., Sedghi, M. (2021). Study of expression pattern of some transcription factors in wheat under drought stress and zinc nanoparticles. *Plant Genet. Res.* 7, 135–144. doi: 10.52547/pgr.7.2.11
215. Yan, W., Zhong, Y., Shangguan, Z. (2016). A meta-analysis of leaf gas exchange and water status responses to drought. *Sci. Rep.* 6, 1–9. doi: 10.1038/srep20917
216. Yang, K.-Y., Doxey, S., Mclean, J. E., Britt, D., Watson, A., Al Qassy, D., et al. (2018). Remodeling of root morphology by CuO and ZnO nanoparticles: effects on drought tolerance for plants colonized by a beneficial pseudomonad. *Botany* 96, 175–186. doi: 10.1139/cjb-2017-0124
217. Yasmeen, F., Raja, N. I., Razzaq, A., Komatsu, S. (2017). Proteomic and physiological analyses of wheat seeds exposed to copper and iron nanoparticles. *Biochim. Biophys. Acta (BBA)-Prot. Prot.* 1865, 28–42. doi: 10.1016/j.bbapap.2016.10.001
218. Yuan, Z., Ye, Y., Gao, F., Yuan, H., Lan, M., Lou, K., et al. (2013). Chitosan-graft- β -cyclodextrin nanoparticles as a carrier for controlled drug release. *Int. J. Pharmaceut.* 446 (1-2), 191–198. doi: 10.1016/j.ijpharm.2013.02.024
219. Zahedi, S. M., Hosseini, M. S., Daneshvar Hakimi Meybodi, N., Peijnenburg, W. (2021). Mitigation of the effect of drought on growth and yield of pomegranates by foliar spraying of different sizes of selenium nanoparticles. *J. Sci. Food Agricul.* 101, 5202–5213. doi: 10.1002/jsfa.11167
220. Zahedi, S. M., Hosseini, M. S., Meybodi, N. D. H., Da Silva, J. (2019). Foliar application of selenium and nano-selenium affects pomegranate (*Punica granatum* cv. malase saveh) fruit yield and quality. *South Afri. J. Bot.* 124, 350–358. doi: 10.1016/j.sajb.2019.05.019
221. Zahedi, S. M., Karimi, M., Teixeira Da Silva, J. A. (2020a). The use of nanotechnology to increase quality and yield of fruit crops. *J. Sci. Food Agricul.* 100, 25–31. doi: 10.1002/jsfa.10004
222. Zahedi, S. M., Moharrami, F., Sarikhani, S., Padervand, M. (2020b). Selenium and silica nanostructure-based recovery of strawberry plants subjected to drought stress. *Sci. Rep.* 10, 1–18. doi: 10.1038/s41598-020-74273-9
223. Zahedi, S.M.; Hosseini, M.S.; Meybodi, N.D.H.; Peijnenburg, W. Mitigation of the effect of drought

- on growth and yield of pomegranates by foliar spraying of different sizes of selenium nanoparticles. *J. Sci. Food Agric.* 2021, 101, 5202–5213.
224. Ze, Y., Liu, C., Wang, L., Hong, M., Hong, F. (2011). The regulation of TiO₂ nanoparticles on the Manzoor N, Ali L, Ahmed T, Noman M, Adrees M, Shahid MS, Ogunyemi SO, Radwan KSA, Wang G and Zaki HEM (2022) Recent Advancements and Development in Nano-Enabled Agriculture for Improving Abiotic Stress Tolerance in Plants. *Front. Plant Sci.* 13:951752. doi: 10.3389/fpls.2022.951752
- expression of light-harvesting complex II and photosynthesis of chloroplasts of *Arabidopsis thaliana*. *Biol. Trace Ele. Res.* 143, 1131–1141. doi: 10.1007/s12011-010-8901-0
225. Zhang, C., Hu, Z., Li, P., & Gajaraj, S. (2016). Governing factors affecting the impacts of silver nanoparticles on wastewater treatment. *Science of the Total Environment*, 572, 852-873.
226. Zhang, H.; Zhao, Y.; Zhu, J.-K. Thriving under Stress: How Plants Balance Growth and the Stress Response. *Dev. Cell* 2020, 55, 529–543.
227. Zhang, L. W., Monteiro-Riviere, N. A. (2009). Mechanisms of quantum dot nanoparticle cellular uptake. *Toxicol. Sci.* 110, 138–155. doi: 10.1093/toxsci/kfp087
228. Zhang, Y., Liu, N., Wang, W., Sun, J., Zhu, L. (2020). Photosynthesis and related metabolic mechanism of promoted rice (*Oryza sativa* L.) growth by TiO₂ nanoparticles. *Front. Environ. Sci. Engin.* 14, 1–12. doi: 10.1007/s11783-020-1282-5
229. Zhang, Z., Kong, F., Vardhanabhuti, B., Mustapha, A., Lin, M. (2012). Detection of engineered silver nanoparticle contamination in pears. *J. Agric. Food Chem.* 60, 10762–10767. doi: 10.1021/jf303423q
230. Zhao, J.; Lu, Z.; Wang, L.; Jin, B. Plant responses to heat stress: Physiology, transcription, noncoding RNAs, and epigenetics. *Int. J. Mol. Sci.* 2020, 22, 117.
231. Zhao, L.-S., Li, K., Wang, Q.-M., Song, X.-Y., Su, H.-N., Xie, B.-B., et al. (2017). Nitrogen starvation impacts the photosynthetic performance of *Porphyridium cruentum* as revealed by chlorophyll a fluorescence. *Sci. Rep.* 7, 1–11. doi: 10.1038/s41598-017-08428-6
232. Zulfiqar, F.; Ashraf, M. Nanoparticles potentially mediate salt stress tolerance in plants. *Plant Physiol. Biochem.* 2021, 160, 257–268. Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, Sadia S Nasim W, Adkins S, Saud S, Ihsan MZ, Alharby
233. H, Wu C, Wang D and Huang J (2017) Crop Production under Drought and Heat Stress: Plant Responses and Management Options. *Front. Plant Sci.* 8:1147. doi: 10.3389/fpls.2017.01147.
234. Joudeh, N., Linke, D. Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *J Nanobiotechnol.* 20, 262 (2022). <https://doi.org/10.1186/s12951-022-01477-8>
