

A Review on Modulation of Plant Growth by Nanoparticles: Application in Agriculture and Mitigation of Environmental Pollution

Dr Vijay Kumar Sinhal^{1*}, Dr Pankaj Kumar Arora², Prof Sanjay Kumar Garg³, Prof JN Maurya⁴, Prof Vijay Pal Singh⁵, Dr. Ranjeet Singh⁶, Prof. Alok Srivastava⁷

^{1,2}Associate Professor, Department of Plant Science, M.J.P. Rohilkhand University, Bareilly, UP, India

³Dean, Faculty of Applied Science, Department of Plant Science, M.J.P. Rohilkhand University, Bareilly, UP, India

⁴Department of Plant Science, M.J.P. Rohilkhand University, Bareilly, UP, India

⁵Ex. Pro Vice-Chancellor & Head, Department of Plant Science, M.J.P. Rohilkhand University, Bareilly, UP, India

⁶Department of Horticulture, KrishiVikas Kendra, ICAR-IVRI, Izzatnagar, Bareilly UP

⁷Head, Department of Plant Science, M.J.P. Rohilkhand University, Bareilly, UP, India

*Corresponding Author

A Review on Modulation of Plant Growth by Nanoparticles: Application in Agriculture and Mitigation of Environmental Pollution.

Vijay Kumar Sinhal¹ Pankaj Kumar Arora¹ Sanjay Kumar Garg¹ Vijay Pal Singh¹ Ranjeet Singh² and Alok Srivastava¹

1- Department of Plant Science, MJPRU, Bareilly

2- Department of Horticulture, KrishiVikas Kendra, ICAR-IVRI, Izzatnagar, Bareilly UP

ABSTRACT

By applying nanoparticles in agriculture, we can remediate the polluted soil and increase crop productivity. It can also decrease mineral loss and can lessen fertilizer use. In recent years, the convergence of nanotechnology and agriculture has opened new avenues for enhancing crop production, stress tolerance, and overall plant performance. Nanoparticles are indeed defined as particles with dimensions typically ranging from 1 to 100 nanometres. Due to their small size, nanoparticles have a significantly larger surface area relative to their volume compared to bulk materials. Due to such unique properties, nanoparticles can interact with biological systems, including plants, in ways that hold immense promise for modern agriculture. The investigation into the role of nanoparticles in regulating plant growth has evolved into a captivating area of study, offering promising pathways to tackle key challenges in agriculture. These challenges encompass, among others, food security, environmental sustainability, and resource efficiency. The present review article explains how nanoparticles can serve as effective delivery vehicles for PGRs. Such nanoparticle-PGR synergy allows the modulation of overall plant growth. The article also investigates the mechanism of nanoparticle uptake and its influence on phytohormones. Thus, the present article states that future research should focus on environmental fate, safety assessment, standardized regulations, and ethical implications of nanoparticle applications in agriculture.

Keywords- Environment, Heavy metal, Nanoparticles, Plant growth regulators, Pollution.

Article Highlights-

- 1- Due to their small size and large surface area nanoparticles can interact with the biological system and affect plant growth. Nanoparticles can serve as effective delivery vehicles for plant growth regulators.
- 2- Nanoparticles in the form of nano fertilizers can increase nutrient uptake, resulting in reduced nutrient loss, improved crop quality, enhanced yield, and minimized environmental degradation risks.
- 3- Nanoparticles have opened up new possibilities for improving food safety and extending the shelf life of food products. Silver and zinc oxide nanoparticles incorporated into food packaging materials have antimicrobial activities. They can inhibit the growth of bacteria, fungi, and other microorganisms that can spoil food.

INTRODUCTION

In recent times, the synergy of nanotechnology and agriculture has opened new lines for enhancing crop yield, stress tolerance, and overall plant growth [1,2,3]. Nanoparticles can be broadly categorized into inorganic nanoparticles and organic nanoparticles. The inorganic nanoparticles are comprised of a metal or non-metal element or take the form of

an oxide, hydroxide, or phosphate compound. Organic nanoparticles are entirely composed of carbon atoms arranged in a hollow sphere, ellipsoid, or tube. Among inorganic nanoparticles, magnetic nanoparticles are typically composed of materials like iron oxide. The role of nanoparticles in plant growth modulation has emerged as an engrossing area of research, offering potential solutions to critical challenges in agriculture, such as food security, environmental sustainability, and resource efficiency [4].

The present review article focuses on the tangled interaction between nanoparticles and plant growth regulators (PGRs), shedding light on the mechanisms that underpin their interactions and the applications that arise from such interactions.

The term "plant growth regulators" designates a diverse group of small molecules, often referred to as phytohormones, which regulate various metabolic processes in plants. These processes include seed germination, root and shoot growth, flowering, fruiting, and responses to environmental stresses. There are many plant growth regulators like IAA, GAs, ABA, and ethylene, which have their distinct role and signaling pathways [5, 6].

Furthermore, nanoparticle-mediated regulation of phytohormones extends beyond growth promotion. Nanoparticles have been explored for their role in stress-responsive hormone pathways, such as abscisic acid, which orchestrates plants' responses to drought and other environmental challenges. By harnessing nanoparticles to fine-tune hormone levels and signaling, researchers aim to create plants with enhanced resilience to environmental stresses [7, 8].

Nanoparticles-

Based on composition, nanoparticles can be categorized as organic, carbon-based, and inorganic (Fig-01):-

(i)-Organic Nanoparticles

Organic nanoparticles are a diverse class of nanoparticles that are composed primarily of organic compounds (Like Dendrimer, layered biopolymer, Liposome etc). These can be designed and engineered for various applications including drug delivery, diagnostics, and nanotechnology. Some common types of nanoparticles are lipid nanoparticles, polymeric nanoparticles, protein nanoparticles, carbohydrate nanoparticles, nucleic acid nanoparticles, fatty acid nanoparticles, etc. Lipid nanoparticles are used for drug delivery because they can encapsulate hydrophobic drugs and protect them from degradation. Lipid nanoparticles have been utilized in the development of mRNA-based COVID-19 vaccines. Polymeric nanoparticles are composed of biocompatible polymers such as Chitosan, Poly lactic-co-glycolic acid, or Polylactic acid. They also can be in a drug delivery system and can be engineered to release drugs over a controlled period. Carbohydrate-based nanoparticles can be formed using materials like chitosan, dextran, or starch. They are used for drug delivery, vaccine development, and as carriers for imaging agents. Nucleic acid nanoparticles are used for gene delivery and gene therapy applications. They can be engineered to carry specific genetic material into target cells. Some nanoparticles have a hollow core, e.g. liposome. Organic nanoparticles are responsive to both thermal and electromagnetic radiations, including heat and light. Presently, these nanoparticles are extensively utilized in the biomedical field, especially for targeted drug delivery and cancer therapy applications. [9, 10].

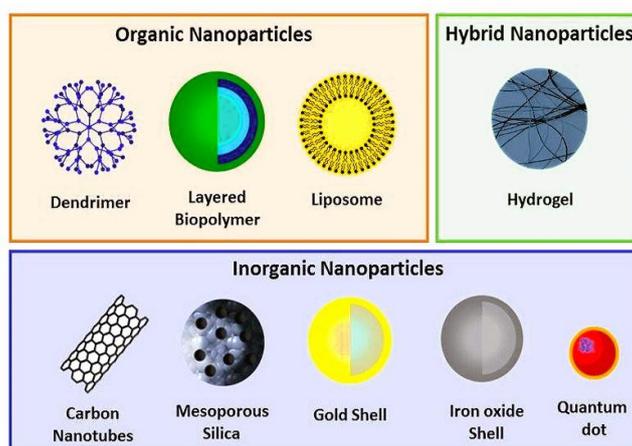


Fig 1 – Different types of Nanoparticles

(ii)-Carbon-based Nanoparticles-

Carbon-based nanoparticles are tiny particles composed, primarily of carbon atoms. They can take various forms including fullerenes, carbon nanotubes and graphene. Nanotubes have unique properties due to their nanoscale size and carbon composition, making them more valuable for commercial and research purposes. Carbon nanotubes are known for their exceptional strength, and electric conductivity, while graphene is a single layer of carbon atoms with remarkable thermal and electrical properties. Researchers continue to explore the potential of carbon-based nanoparticles in fields such as drug delivery and material engineering. Fullerenes are a specific type of carbon-based

nanoparticles that also consist of carbon atoms that are arranged in a closed hollow sphere. Sometimes also shows cage-like structure. The most common and well-known, fullerenes are C₆₀, C₇₀, and C₅₀ [11].

(iii)-Inorganic nanoparticles:

According to Khan et al. [12] inorganic nanoparticles are nanoparticles that are composed of materials other than carbon-based compounds like carbon nanotubes, quantum dots, mesoporous silica, gold shell, iron oxide shell etc (Fig-01). Such nanoparticles are typically made of inorganic elements or compounds and they are widely utilized in different fields. Metal nanoparticles, quantum dots, silica nanoparticles, and magnetic, and ceramic nanoparticles are examples of some common types of inorganic nanoparticles. According to Mody et al. [13] metal nanoparticles are typically composed of metals like gold, silver, platinum, or iron. They are used in various applications, like catalysis, drug delivery, imaging, and as antimicrobial agents. The quantum dots are semiconductor nanoparticles with unique electronic properties. They are being used in electronics, solar cells, and biological imaging [14,15] concluded that ceramic nanoparticles are extremely small particles consisting of ceramic materials. Ceramic nanoparticles exist in various structures, such as amorphous, polycrystalline, dense, porous, or hollow forms. Primarily employed in biomedical applications, these nanoparticles are favoured for their exceptional stability and robust load-bearing capacity.

Characterization of Nanoparticles

The characterization of nanoparticles is a very important step in understanding their structure, properties, and their suitability for various applications. The study of the characterization of nanoparticles can be done by different methods, like morphological analysis, size distribution, chemical composition, surface area & porosity, crystallinity, zeta potential, UV visible-spectroscopy, magnetic properties, surface functional groups, and toxicity assessments of NPs [16,17]. Some common methods of characterization of nanoparticles are as follows-

(a)-Morphological Analysis: Key techniques such as dynamic light scattering, transmission electron microscopy, and scanning electron microscopy are essential for acquiring information about the size, shape, and surface characteristics of nanoparticles.

(b)- Chemical Composition-

The chemical composition of nanoparticles is efficiently determined by energy-dispersive X-ray spectroscopy or X-ray photoelectron spectroscopy.

(c)- Surface Charge-

The surface area of a nanoparticle is an important attribute for catalysis and reactivity. Brunauer- Emmett- Teller (BET) analysis using nitrogen adsorption is a common method for analyzing the surface area of nanoparticles.

(d) Crystallinity-

The crystalline structure of nanoparticles is determined by X-ray diffraction technique.

(e) Magnetic Properties-

Depending on the size, composition, and structure, nanoparticles have some important magnetic properties like superparamagnetism, ferromagnetism, ferrimagnetism, and antiferromagnetism. Superparamagnetism is a phenomenon, observed in nanoparticles with sizes typically less than 30 nanometers. Superparamagnetic nanoparticles contain magnetic domains that align with an applied magnetic field but return to a random orientation when the field is removed. Superparamagnetic nanoparticles have no permanent magnetic moment, making them more useful in magnetic resonance imaging (MRI) and drug delivery. Some nanoparticles composed of ferromagnetic materials like iron, nickel, or cobalt can retain a permanent magnetic moment. They are used in applications such as data storage and magnetic sensors. Ferrimagnetic nanoparticles (ferrites) exhibit a net magnetic moment, but it is smaller than that of ferromagnetic materials. They are used in various technologies including magnetic memory devices and microwave components. Antiferromagnetic nanoparticles contain magnetic moments that align in opposite directions, resulting in a net magnetization of zero. They have potential applications in technologies like spintronics and magnetic sensors.

Environmental and Ecological Considerations of Nanoparticles

Nanoparticles are recognized for their unique properties and their capacity to enhance various products with specific functions, playing a crucial role in advancing sophisticated material technologies for sustainable environmental development. However, the utilization of nanoparticles also poses significant concerns regarding safety and environmental impact. It is vital to consider their effects on human health as well. The application of nanoparticles in sectors like agriculture, medicine, and cosmetics necessitates a thorough understanding of their origins, which can be accidental, artificial, or natural. The diverse origins of nanoparticles contribute to their varied properties and functions, leading to different impacts on the environment. This includes effects from natural processes, such as combustion (e.g., smoke from cigarettes or fire), or industrial processes. Artificially synthesized nanoparticles are designed by humans for their needs with determined properties and characteristics (e.g. silver nanoparticles in shampoo). The prominence of antibiotic resistance among various microorganisms is a significant global health concern. As Bacteria and other

microorganisms develop resistance to traditional antibiotics, it becomes increasingly challenging to treat serious infections effectively. The metallic nanoparticles have unique antimicrobial properties. So they can be used as an alternative adjuvant treatment strategy for bacterial treatments.[18, 19].Zinc nanoparticles have gained attention for their potential antimicrobial properties, including their ability to reduce the growth of microbes, especially bacteria by generating reactive oxygen (ROS) species, particularly hydrogen peroxide. The high surface area of these metal nanoparticles makes them suitable for various applications including antimicrobial activities. Zhang et al. [20] noticed that when Zinc nanoparticles come in contact with microbes they can undergo redox reactions that result in the formation of ROS (Reactive oxygen species).Among the various reactive oxygen species generated, hydrogen peroxide is of particular interest in reducing the growth of bacteria by damaging the cell membrane and intracellular components of bacterial cells. Such damage can lead to cell death and inhibition of bacterial growth. The oxidative stress can damage proteins, DNA, and other cellular structural components essential for bacterial survival.Naturally produced nanoparticles are found in living beings. It is difficult to draw a definite line that separates natural or accidental materials on certain occasions and is very difficult to differentiate from each other.

Nanoparticles have opened up new possibilities for improving food safety and extending the shelf life of food products. Silver and zinc oxide nanoparticles incorporated into food packaging materials have antimicrobial activities. They can inhibit the growth of bacteria, fungi, and other microorganisms that can spoil food. Nanocomposite packaging can enhance the shelf life of perishable foods.Nano-emulsions are colloidal systems in which oil droplets are reduced to nanoscale. They can be used to encapsulate bioactive compounds, vitamins or essential oils that have antimicrobial or antioxidant properties. These nanoemulsions can be added to food products to extend their shelf life and announce their nutritional value. Nanoparticles can be used to create a protective coating on the surface of fruits and vegetables these coating scans Slow Down moisture loss and oxidation, preserving the freshness of the product for a longer period.[21].

Nanoparticle Uptake and Internalization by Plant

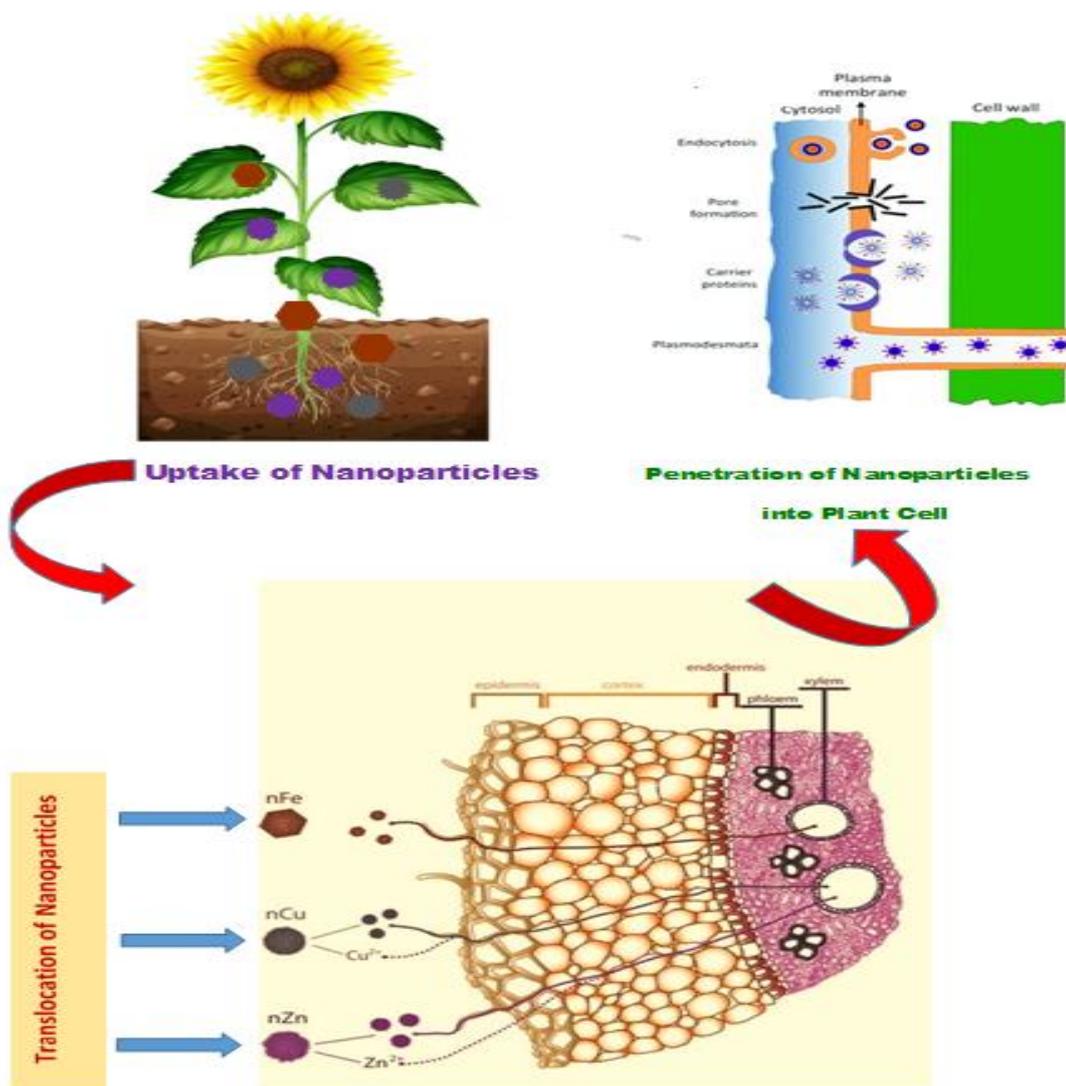


Fig 2: Schematic diagram of the uptake and translocation pathways of NPs in plant

The uptake of nanoparticles by plants is a very interesting interplay between the unique characteristics of nanoparticles and various physiological processes of plants. During uptake, nanoparticles adhere to the surface of root cells due to electrostatic forces, Van der Waals interactions, and chemical bondings. Some nanoparticles can penetrate the root cell walls and membranes. The tiny size of nanoparticles facilitates their entry into the plant tissues. These nanoparticles can be taken up by plant cells through endocytosis. It is a process in which the cell membrane engulfs the nanoparticles forming vesicles that are then transported into the cells. Once nanoparticles enter into the root cell, move inside the plant through vascular tissues. Nanoparticles can accumulate in various plant organs (Fig.-02). There are various factors such as size shape surface charge and chemical composition of nanoparticles influence the accumulation of nanoparticles in plants. Recently, many workers started working on engineered nanomaterial (ENM), their uptake, and their environmental interaction. Schwab et al. [22], noticed that the uptake of nanoparticles through the plant cell membrane likely involves two alternative pathways: 'Endocytosis' and 'Non-endocytic.' The selection between these pathways depends on the dimensions (size and shape) and surface charge of the entering particles.

Endocytosis is a cellular process wherein cells internalize external materials by enveloping them with the cell membrane. A likely pathway for the internalization of positively charged nanoparticles is receptor-mediated clathrin-dependent fluid-phase endocytosis (CFPE), as suggested by Etxeberria et al. [23]. This CFPE pathway typically involves small clathrin-coated vesicles approximately 70–120 nm in diameter. For instance, oxidized SWCNTs (single-walled carbon nanotubes) shorter than 500 nm can traverse the plant cell membranes of *Nicotianatobaccum*, as observed by Rico et al. [24]. Additionally, non-endocytic pathways, predominantly water channels, have been proposed to facilitate nanoparticle uptake routes. Khodakovskaya et al. [25] found that upon exposure to nanoparticles, aquaporin activity might increase the transport of nanoparticles. This observation aligns with similar findings by Lu et al. [26], and Taylor et al. [27]. Nanoparticles may obstruct the apoplast pathway, potentially reducing water flow through the plant system and altering the functionality of aquaporins, as noticed by Lu et al. [26] and Ranathunge et al. [28].

Role of Nanoparticles in Hormone Signalling Pathways

Nanoparticles' interactions with hormone signaling pathways have far-reaching implications for plant growth, development, and responses to environmental stressors. These interactions can influence hormone biosynthesis, perception, and downstream signaling events, ultimately shaping plant physiological responses. Here, we delve into the role of nanoparticles in hormone signaling pathways, highlighting their effects on hormone biosynthesis, perception, and crosstalk, supported by relevant references.

(i) Regulation of Hormone Biosynthesis:

Plant growth hormones or plant growth regulators like auxin, cytokinin, abscisic acid, salicylic acid, gibberellic acid, jasmonic acid, etc. act as endogenous signaling molecules that play a major role in the growth and developmental response in plants [29,30], noticed that phytohormones, including abscisic acid, jasmonic acid, salicylic acid, and ethylene, play vital roles in the regulation of plant defence systems against both biotic and abiotic pollutants. Vankova et al. [31], applied different concentrations (Range 0.16-100 mg L⁻¹) of 30 nm sized nanoparticles on *Arabidopsis thaliana* plant to assess the impacts of these nanoparticles on the synthesis of main phytohormones (auxins, cytokinins, salicylic acids, jasmonic acid and abscisic acid) in different plant parts. The biosynthesis of growth regulators such as cytokinins and auxins in shoot apical meristems was gradually suppressed with an increase in nanoparticle concentration. Meanwhile, cis-zeatin, a cytokinin linked to stress responses, exhibited a significant increase of 280% and 590% in roots when exposed to nanoparticle concentrations of 20 mg L⁻¹ and 100 mg L⁻¹, respectively. The conclusion drawn is that at low concentrations, nanoparticles induce the biosynthesis of phytohormones, specifically cytokinins. However, at moderate to high doses, zinc oxide nanoparticles act as stress agents, triggering plant defense mechanisms. This response is closely linked to a significant up-regulation of stress hormones such as abscisic acid and salicylic acid. Different workers in their studies evidenced the interactions between nanomaterials and plant growth hormones [32], however, investigations about molecular mechanisms concerned with nanoparticles and plant growth regulator interactions are still to be more elaborate.

(ii) Modification of Hormone Perception:

In the relation to hormone perceptions, nanoparticles can be designed and utilized to modify or influence how cells respond to hormones. Here are some ways in which nanoparticles may be involved in the modification of hormone perception-

- (a) Nanoparticles can be engineered to encapsulate hormones and deliver them to specific target cells or tissues. Such targeted delivery can enhance the efficiency of hormone action while minimizing the side effects on non-target tissues.
- (b) Nanoparticles interact with ligands that mimic the structure of hormone receptors. Such surface modifications may enhance the interaction between nanoparticle and cell receptors potentially affecting the cellular response to hormones.
- (c) Nanoparticles can protect hormones from degradation by enzymes. Thus ensures a longer half-life and sustains the physiological effects of hormones.
- (d) Nanoparticles can be engineered to interfere with or enhance the binding of hormones to their respective receptors. Such modulation may either inhibit or potentiate the cellular response to hormones.

- (e) Some engineered nanoparticles are capable of penetrating the cell and releasing their cargo directly into the cell's interior.
- (f) Nanoparticles can incorporate sensor platforms for detecting hormone levels. The hormone concentrations can be detected by these sensors and thus allow timely adjustment in hormone therapy or monitoring.

It is important to note that while these applications promise, there are some challenges and potential risks associated with the use of nanoparticles such as toxicity, biocompatibility, and long-term effects. Further, much more researches are needed to fully understand the implications of using nanoparticles for modifying hormone perception and to ensure their safe and fruitful application in agriculture and medical fields

(iii) Crosstalk between Hormones-

The interplay between plant hormones is crucial for the regulation of various physiological processes in plants. Nanoparticles have gained attention in recent years for their potential role in mediating cross-talk between plant hormones. Nanomaterials, particularly nanoparticles, nanotubes, and nanosheets, can interact with plant cells and influence hormone signaling pathways. Nanoparticles can be used as potential carriers for targeted delivery of plant hormones. This may result in controlled release and better uptake by plant cells. Such targeted delivery can enhance the efficiency of hormonal treatments and effectively influence the cross-talk between different hormones. Further, nanoparticles can improve the absorption of hormones by plant cells. They can penetrate the plant cell wall and enable the hormones to enter the cell more potentially. Several research findings suggest that nanoparticles can intensify the antagonistic interaction between abscisic acid and jasmonic acid, consequently affecting how plants respond to biotic stress. Tripathi et al. [33], concluded that Plant growth hormones function as regulatory molecules during stress and play a role in diverse signaling cascades when exposed to nanoparticles. Under stressful conditions, an excess of reactive oxygen species (ROS) is produced. These nanoparticles can regulate the levels of reactive oxygen species (ROS). Additionally, it has been reported that nanoparticles can mitigate the consequences of stress by regulating phytohormone signalling. Tripathi et al. [7] stated that the elevated activity of the antioxidant enzyme system and hormonal signaling induced by nanoparticle exposure are pivotal factors in regulating the adverse impact of stress in plants.

(iv) Nanoparticles and Stress Responses:

Nanoparticles significantly influence plant stress responses. Studies on various nanoparticles have highlighted their potential in enhancing plant growth, development, and stress resilience (Table-01). These particles interact with multiple physiological, biochemical, and molecular processes in plants, thereby modulating responses to environmental stressors such as drought or pathogens. Nanoparticles, owing to their small size, expansive surface area, multitude of reactive sites, and efficient catalytic capabilities, present a promising approach to initiate biochemical reactions that improve plant eco-physiological performance. In saline conditions, eco-physiological adaptations regulated by nanoparticles could prove vital for the survival of plants under stress. Many researchers, such as Abideen et al. [34], are exploring a wide array of genes and proteins that contribute to salt tolerance. For instance, ZnO nanoparticles have been observed to penetrate plant leaves, accumulating in edible parts and assimilating into the surrounding soil near plant roots. Moreover, nanoparticles have been found to modulate responses associated with abscisic acid during drought stress, influencing stomatal behavior, water-use efficiency, and overall stress tolerance with notable effects [35,12], noticed that upon penetration into the plant via roots and leaves, nanoparticles prompt diverse biochemical, molecular, morphological, and physiological alterations, exerting a significant influence on the growth and development of the plant.

These effects are contingent upon the concentration, size, and application method of the nanoparticles. Research suggests that nanoparticles can allviate the adverse effects of drought stress and significantly enhance plant growth, development, and yield [36,37], noted that drought stress disrupts nutrient uptake and induces deficiencies, adversely affecting plant growth and development [38], Furthermore, applying nanoparticles via soil and foliar spray has been shown to improve the uptake of essential nutrients such as nitrogen, phosphorous, potassium, and zinc, thereby reducing the detrimental effects of drought stress [39,40 41,42].

Table 1: Alleviation of Abiotic stress in plants through different types and sized Nanoparticles.

S.N.	Nanoparticles (NPs)	Size (nm)	Plant species	Type of stress	Effects	References
1	ZnO	10-35	<i>Lycopersicon esculantum</i>	Drought stress	Rate of germination and percentage increased	[43]
2	ZnO & Si	ZnO < 100nm SiNP 5-15 nm	<i>Mangifera indica</i>	Salinity stress	Improved plant growth, nutrient uptake and photosynthesis	[44]

3	Fe ₂ O ₃	27-34 nm	<i>Menthapiperita</i>	Salinity stress	Reduced proline and MDA levels, suppressed the activity of antioxidant enzymes	[45]
4	Fe ₃ O ₄	40-55 nm	<i>Fragariaxenanasa</i>	Drought stress	Enhanced shoot growth parameters	[46]
5	Fe ₂ O ₃	20-40 nm	<i>Dracocenthalum moldavica</i>	Salinity stress	Increased leaf area, phenolic, flavonoid & anthocyanin content, and activity of antioxidant enzymes like APX, CAT, SOD etc.	[47]
6	Biogenic AgNPs	NA	<i>Solanumlycopersicum</i>	Salinity stress	Improved seed germination	[48]
7	AgNPs	NA	<i>Raphanussativus</i>	Heavy metal stress	Heavy metals (Cr, Cu, Fe, Pb, & Zn) uptake is regulated by AgNPs present in wastewater	[49]
8	AgNPs	NA	<i>Taraxacumofficinale</i>	Oxidative stress	Reduced harmful effects of reactive oxygen species	[50]
10	TiO ₂	07-40 nm	<i>Cicer arietinum</i>	Cold Stress	Decreased electrolyte leakage index and MDA levels	[51]
11	SiO ₂	20 nm	<i>Solanumlycopersicum</i>	Salinity stress	Improved vegetative growth. Salt stress genes were up and down-regulated significantly to help alleviate the salt stress	[52]
12	FeNPs	50-100 nm	<i>Triticumaestivum</i>	Cadmium and Drought stress	Improved carbon assimilation and plant growth. Reduced Cadmium concentration and Drought stress.	[53]

(v) Nanoformulations of Synthetic PGRs:

Plant growth regulators (PGRs) play a crucial role in agriculture by manipulating hormonal balance and regulating different stages of plant growth and development. The introduction of modified release systems using polymers has provided innovative approaches to enhance the efficiency of these compounds. Current research is focused on utilizing polymeric particles as carriers for PGRs, enabling controlled release and protecting them from degradation. A notable application is the deployment of polymeric nanoparticles for delivering phytohormones, such as gibberellic acid, which have demonstrated enhanced efficiency in boosting seed germination and seedling growth compared to their non-nanoparticulate counterparts. Furthermore, nanoparticles engineered to release salicylic acid (SA) and nitric oxide have been effective as plant protection agents under various stress conditions. Additionally, polymeric materials like chitosan have been used to alter plant signaling pathways favorably, thereby promoting growth and development. This strategy presents considerable promise for improving plant productivity while minimizing environmental impact [54]. Ultimately, nanoparticle-based formulations provide a controlled and sustained release of PGRs, ensuring a consistent and prolonged availability of these vital compounds.

This controlled release offers several benefits:

(i) Enhanced Efficacy: Controlled release ensures that PGRs are available to plants gradually over an extended duration, allowing for optimal responses without abrupt spikes in hormone concentrations.

- (ii) **Reduced Application Frequency:** The prolonged action of PGRs reduces the need for frequent applications, resulting in decreased labor and operational costs associated with application.
- (iii) **Minimized Environmental Impact:** Controlled release mitigates the overuse of PGRs, minimizing environmental impact and potential negative effects on non-target organisms.
- (iv) **Solubility Enhancement:** Nanoparticles improve the solubility of hydrophobic PGRs, making them readily available for uptake by plant tissues.

Application of Nanotechnology in Agriculture

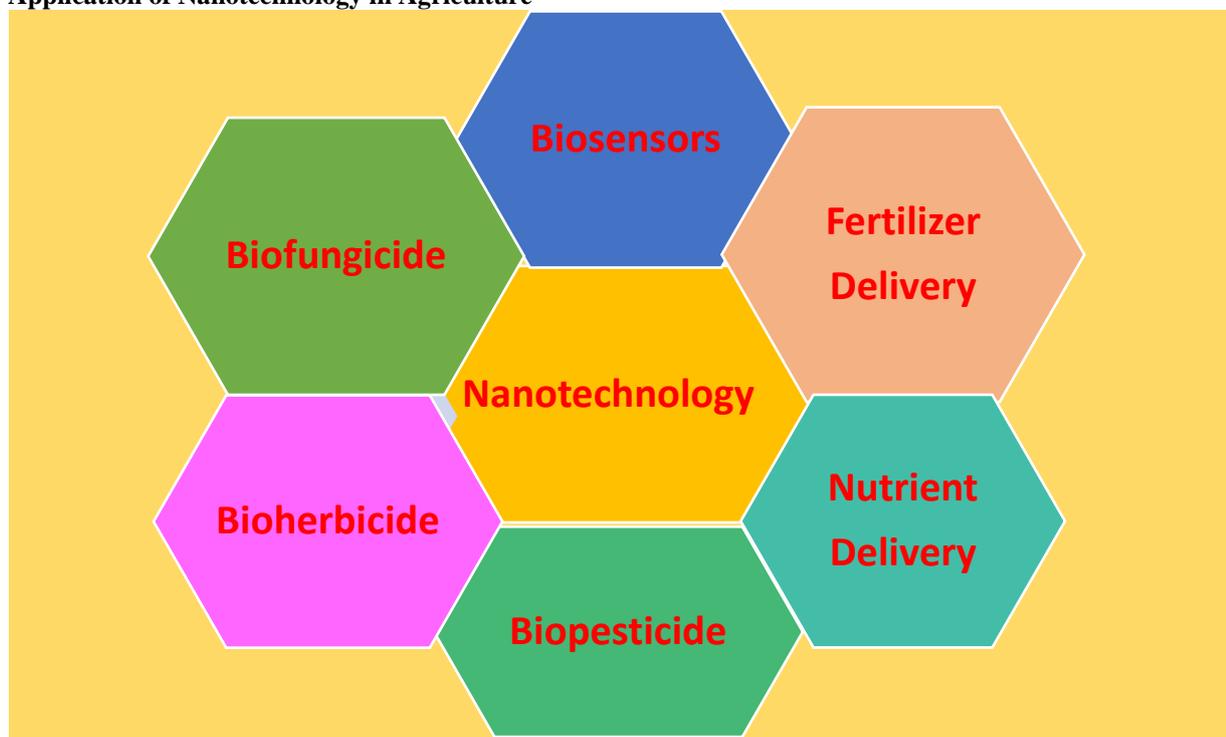


Fig 3-Application of Nanotechnology

In agriculture nanomaterials are applied in the form of biofungicide, bioherbicide, biosensors and biopesticide. They also involved in fertilizer and nutrient delivery (Fig-03). Thus, Nanotechnology is crucial in agriculture, offering innovative solutions to enhance various aspects of crop production, soil management, and pest control. The integration of nanoscale materials and techniques in agriculture has the potential to revolutionize the industry in the following ways:

(a) Precision Farming: Nanosensors and nanodevices enable real-time monitoring of soil conditions, crop health, and environmental parameters. This facilitates precision farming, allowing farmers to optimize resource utilization and make informed decisions for efficient crop management [55].

(b) Improved Crop Yield and Quality: Nano-fertilizers and nanopesticides enable targeted delivery of nutrients and plant protection agents. This boosts the absorption of nutrients, minimizes waste, and enhances the effectiveness of pest control measures, ultimately resulting in higher crop yield and improved quality.

(c) Water Management: Nanotechnology contributes to the development of smart irrigation systems that optimize water usage. Nanoscale materials can improve soil water retention, reducing the need for excessive irrigation and promoting sustainable water management practices.

(d) Disease Detection and Treatment: Nanoscale biosensors aid in the early detection of plant diseases, allowing for prompt intervention. Nanoparticles can also serve as carriers for delivering antimicrobial agents or genetic material to enhance plant resistance against pathogens [56].

(e) Soil Remediation: Nanomaterials are employed for soil remediation by facilitating the removal of contaminants and improving soil structure. Nano-enabled soil amendments can enhance nutrient availability and support plant growth in degraded or polluted soils [55]

(f) Seed Enhancement: Nano-coatings on seeds can protect against pests, pathogens, and environmental stressors. These coatings may also include nanocarriers for controlled release of nutrients, promoting seed germination and early seedling development.

(g) Post-Harvest Preservation: Nanotechnology contributes to the development of nanomaterial-based packaging and storage solutions that extend the shelf life of agricultural products. This helps reduce post-harvest losses and ensures the availability of fresh produce for longer periods.

(h) Solar Energy Utilization: Nanomaterials, such as nanoparticles for enhancing photosynthesis or nanocomposites for solar-driven water splitting, can be employed to harness solar energy more efficiently, providing sustainable energy sources for agricultural practices.

(i) Nanofertilizers: Nano fertilizers are designed to supply nutrients to plants or augment the efficacy of fertilizers even when administered in reduced quantities. Encapsulating fertilizers in nano form can increase the nutrient uptake, resulting in reduced nutrient loss, improved crop quality and enhanced yield, and minimized environmental degradation risks. Additionally, the foliar application of such nano fertilizers has been shown to alleviate stress in plants. [57]. Nanofertilizers have diverse origin and applications. Different types of nano fertilizers and their effects on growth and yield in different crop plants is listed in Table 02. On the basis of nutritional requirements of plants, nanofertilizers can be divided into three categories (1) macronutrient nano fertilizers, (2) micronutrient nano fertilizers, and (3) nanoparticulate nano fertilizers [58]. Macronutrient nano fertilizers are composed of a combination of macroelements, such as potassium (K), magnesium (Mg), nitrogen (N), calcium (Ca), and phosphorus (P). It is noticed that the total consumption of macronutrient fertilizers is projected to increase to 263 million tons (Mt) in 2050, thus exhibiting a critical need for these fertilizers in the agricultural sector. Delfani and his coworkers estimated the efficiency of Mg and Fe NPs on the growth of black-eyed peas (*Vigna unguiculata*) by foliar application and observed increased seed weight and photosynthetic ability that, in turn, increased the yield [59]. The inclusion of calcium nanoparticles (Ca NPs) in conjunction with humic acids significantly enhanced seedling growth in peanuts, resulting in an approximate 30% increase. The dry biomass per plant reached 5.78 grams [60]. The hydroxyapatite nanoparticles [Ca₅(PO₄)₃OH] synthesized, with a size of 16 nm, markedly boosted the growth rate and yield of soybeans (*Glycine max*) compared to the control group. These findings indicate the potential application of nanoparticles as effective fertilizers for field crops [61]. Some important

Table 2: Application of different Nanoparticles as Nanofertilizers in different crop plants.

S.N.	Nanoparticles (NPs)	Size (nm)	Plant species	Effects on Crop Plants	References
1	ZnO NPs	NA	<i>Mungbean (Vigna radiate)</i>	Foliar application of nano-fertilizers enhanced the biomass of roots & shoots.	[62]
2	ZnO NPs	25 nm 50-2000 ppm concentration	<i>Zea mays</i>	Germination percentage increased upto 80% at 1500ppm. Grain yield was highest (3.298 kg/ha) at 400ppm.	[63]
3	FeOXNPs	05-20 mg/L	<i>Lectucasativa</i> (Lettuce)	12-26% shoot length increased significantly.	[64]
4	Fe ₂ O ₃ NPs	30-60 mg/L	<i>Glycine max</i>	Chlorophyll content was also increased significantly in hydroponically cultivated Soybean plants.	[65]
5	Cu-Chitosan NPs	0.04-0.12%	<i>Zea mays</i>	Enhanced seedling growth.	[63]
6	CuO	150-340 µg/mL	<i>Solanumlycopersicum</i>	Plant growth increased in term of plant height, fresh & dry weight.	[66]
7	AgNPs	5,10,20,50, 100 mg/L	<i>Solanummelangena</i>	Growth parameters (shoot & root height, fresh & dry weight of root and shoot), and biochemical parameters (chlorophyll a, b & total chlorophyll, total protein, and total lipids) were significantly increased.	[67]

In summary, nanotechnology in agriculture is promising to address the challenges of food security, resource efficiency, and environmental sustainability by offering precise and targeted solutions across various stages of the agricultural value chain.

CONCLUSION

The present article unambiguously declares that nanoparticles act as an efficient tool for delivering plant growth regulators to the targeted site of action, resulting in enhanced growth and development of plants. Nanoparticles are also able to increase the efficiency of plant growth regulators and thus effectively modulate the mechanism of action of growth regulators. Because of their small size and expansive surface area, nanoparticles possess the capability to interact with biological systems, particularly plants, thereby potentially boosting the productivity of agricultural products. In summary, nanotechnology in agriculture holds great promise for addressing the challenges of food security, resource efficiency, and environmental sustainability by offering precise and targeted solutions across various stages of the agricultural value chain.

Statements & Declarations-

Authors Contribution “All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by [Dr Vijay Kumar Sinhal], and [Dr Pankaj Kumar Arora]. The first draft of the manuscript was written by [Dr Vijay Kumar Sinhal] and other authors viz. Prof Sanjay Kumar Garg, Prof V.P. Singh, and Prof. Alok Srivastava commented on previous versions of the manuscript. All authors read and approved the final manuscript.”

Funding- “The authors declare that no funds, grants, or other support were received during *the preparation of this manuscript.*”

Competing Interests- “The authors have no relevant financial or non-financial interests to disclose.”

REFERENCES

- [1]. Rajput DV Tatiana M Upadhyay SK Kumari A RanjanA Mandzhieva S Sushkova S Singh R KVermaKK2022Nanotechnologyintherestorationofpollutedsoil.Nanomaterials12 769.<https://doi.org/10.3390/nano12050769>.
- [2]. Auffan M Rose J Bottero JY Lowry GV Jolivet JP Wiesner MR 2009 Towards a definition of inorganicnanoparticlesfromanenvironmental,health and safetyerspective.NatNanotechnol 4 634–641
- [3]. -Sinhal VKGarg SKSingh VPSrivastava A 2022 Nano-phytoremediation approach to remediate contaminatedsoil. International Journal of Enhanced Research in Science Technology& Engineering 11 12 148-159
- [4]. Fiol DF Terrile MC Frik J 2021 Nanotechnology in plants: recent advances and challenges. J ChemTechnolBiotechnol96 8 2095–2108
- [5]. Khan N Bano A Ali S Babar M 2020 Crosstalk amongst phytohormones from planta and PGPR under biotic and abiotic stresses. Plant Growth Regul 90 2 189203.
- [6]. SytarO Kumari P Yadav S Brestic M Rastogi A 2019Phytohormone priming: regulator for heavy metal stress in plants. J Plant Growth Regul. 38 2 739–752.
- [7]. Tripathi D Singh M Rai Shashi PR 2022Crosstalk of nanoparticles and phytohormones regulate plant growth and metabolism under abiotic and biotic stress. Plant Stress 6 1 11.
- [8]. Zhou T Prasher S Qi Z George S Mawof A Nzediegwu C Dhiman J Patel R 2021 Impacts of silver nanoparticles in waste water on Heavy metal Transport in soil and uptake by Radish plants. Water Air Soil Pollut 232 267 doi: 10.1007/S 11270-02105227-8 Google Scholar Cross Ref
- [9]. Long CM Nascarella MA Valberg PA 2013 Carbon black vs black carbon and other airborne materials containing elemental carbon: physical and chemical distinctions. Environ Pollut 181 271 286.
- [10]. EaliaSAM Saravanakumar MP 2017 A review on the classification, characterization, synthesis of nanoparticles and their application. In: IOP Conference Series: Materials Science and Engineering IOP Publishing; 2017 p.s32019.
- [11]. Alina A Oscar N Maria TG 2015Characterisation and determination of fullerenes: A critical review.AnalyticaChimicaActa 882 1-21
- [12]. Khan I Saeed K Khan I 2019 Nanoparticles: properties, applications and toxicities. Arab J Chem 12 7 908–31.
- [13]. ModyVV Siwale R Singh A Mody HR 2010 Introduction to metallic nanoparticles. J Pharm BioalliedSci 2 4 282
- [14]. Dreaden EC AlkilanyAM Huang X Murphy CJ El-Sayed MA 2012 The golden age: gold nanoparticles for biomedicine. ChemSoc Rev 417 2740 2779
- [15]. Thomas S Kumar Mishra PTalegaonkar S 2015 Ceramic nanoparticles:fabricationmethods and applications in drug delivery. Curr Pharm Des 21 42 616588
- [16]. Tan S Sherman RL, Ford WT 2004 Nanoscale compression of polymer microspheres by atomic force microscopy. Langmuir 20 17 7015 7020
- [17]. Armini S Vakarelski IU Whelan CM Maex K Higashitani K 2007 Nanoscale indentation of polymer and composite polymer–silica core–shell submicrometer particles by atomic force microscopy. Langmuir 23 414

- [18]. Cao S Rathi P Wu XGhim D Jun Y Singamaneni S 2020 Cellulose Nanomaterials in Interfacial Evaporators for Desalination: A “Natural” Choice Adv Mater CrossRef
- [19]. Miranzadeh M Kassae M Afshari F 2019 Efficiency of Cu, Ag, and Fe Nanoparticles as Detergents Preservatives against E. coli and S. aureus. NanochemRes 4 170–178
- [20]. Zhang L Jiang Y Ding Y Povey M York D 2007 Investigation into the antibacterial behavior of suspensions of ZnO nanoparticles (ZnO nanofluids). J Nanoparticle Res 9 479–489.
- [21]. Rhim JW Park HM Ha CS 2013 Bio-nanocomposites for food packaging applications. Prog. Polym. Sci. 38 1629–1652.
- [22]. Schwab F Zhai G Kern M Turner A Schnoor JL Wiesner MR 2016 Barriers, pathways, and processes for uptake, translocation and accumulation of nanomaterials in plants—a critical review. Nanotoxicology 10 3 257–278.
- [23]. Etxeberria E Gonzalez P Baroja-Fernandez E Romero JP 2006 Fluid phase endocytic uptake of artificial nanospheres and fluorescent quantum dots by sycamore cultured cells: evidence for the distribution of solutes to different intracellular compartments. Plant Signal Behav 1 4 196–200.
- [24]. Rico CM Majumdar S Duarte-Gardea M Peralta-Videa JRGardea-Torresdey JL 2011 Interaction of nanoparticles with edible plants and their possible implications in the food chain. J Agric Food Chem 59 8 3485–3498.
- [25]. Khodakovskaya MV De Silva KBiris AS Dervishi E Villagarica H 2012 Carbon nanotubes induce growth
- [26]. Lü P Cao J He S Liu J Li H Cheng G Ding Y Joyce DC 2010 Nano-silver pulse treatments improve water relations of cut rose cv. Movie Star flowers. Postharvest BiolTechnol 57 3 196–202.
- [27]. Taylor AF Rylott EL Anderson CW Bruce NC 2014 Investigating the toxicity, uptake, nanoparticle formation and genetic response of plants to gold. PLOS ONE 9 4 e93793.
- [28]. Ranathunge K Steudle E Lafitte R 2005 Blockage of apoplastic bypass-flow of water in rice roots by insoluble salt precipitates analogous to a Pfeffer cell. Plant Cell Environ 28 2 121–133.
- [29]. Sytar O Kumari P Yadav S Brestic MRastogi, A 2019 Phytohormone priming: regulator for heavy metal stress in plants. J. Plant Growth Regul. 38 2 739–752
- [30]. Khan N Bano A Ali S Babar M 2020 Crosstalk amongst phytohormones from plants and PGPR under biotic and abiotic stresses. Plant Growth Regul. 90 2 189–203
- [31]. Vankova T Novak O Strnad M Goessler W Jurasin D Paradišćević N Vrcek I V 2017 Cytokinin response in pepper plants (*Capsicum annum* L.) exposed to silver nanoparticles. Environ Res 156 1018
- [32]. Xie L Chen F Du H Zhang X Wang X Yao G Xu B 2020 Graphene oxide and indole-3-acetic acid cotreatment regulates the root growth of *Brassica napus* L. via multiple phytohormone pathways. BMC Plant Biol 20 1 112
- [33]. Tripathi D Modi A Narayan G Rai SP 2019 Green and cost effective synthesis of silver nanoparticles from endangered medicinal plant *Withania coagulans* and their potential biomedical properties. Mater Sci Eng C 100 152–164.
- [34]. Abedin T 2022 Synthesis of novel tritopic hydrazone ligands: spectroscopy, biological activity, DFT, and molecular docking studies. Molecules, 27 1 22 DOI: <https://doi.org/10.3390/molecules27051656>.
- [35]. Rasheed A Li H Tahir MM Mahmood A Nawaz M Shah AN Aslam MT Negm S Mahmoud MM Hassan MU, and Wu Z 2022 The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. DOI 10.3389/fpls.2022.976179.
- [36]. Ahmed T Noman M Manzoor N Shahid M Abdullah M Ali L 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.
- [37]. Hassan M U Aamer M Umer C M Haiying T Shahzad B Barbanti L 2020 The critical role of zinc in plants facing the drought stress. Agriculture 10 396 doi: 10.3390/agriculture10090396.
- [38]. 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.
- [39]. Akhtar N Ilyas N Meraj T A Pour-Aboughadareh A Sayyed R Mashwani ZUR 2022 Improvement of plant responses by nanobiofertilizer: A step towards sustainable agriculture. Nanomaterials 12 s 965. doi: 10.3390/nano12060965.
- [40]. Fatollahpour GM Rashidi V Mirshekari B Khalilvand BE Farahvash F 2020 Effects of nano-fertilizers on physiological and yield characteristics of pinto bean cultivars under water deficit stress. J Plant Nutr 43 2898–2910. doi: 10.1080/01904167.2020.1799000.
- [41]. Mustafa H Ilyas N Akhtar N Raja N I Zainab T Shah T 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.
- [42]. Semida WM Abdelkhalik A Mohamed GF Abd El-Mageed TAAbd El-Mageed S A, Rady MM 2021 Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena*) Plants 10: 421. doi: 10.3390/plants10020421.
- [43]. Sun Li Song F Guo J Zhu X Liu S Liu F Li X 2020 Nano- ZnO induced drought tolerance is associated with melatonin synthesis and metabolism in Maize. Int. J. Mol. Sci. 21- 782 [Google Scholar][Cross Ref].

- [44]. El-Zohari M Al-Wadaani NA Bafeel SO 2021 Foliar sprayed green zinc oxide nanoparticles mitigate drought-induced oxidative stress in tomato. *Plants* 10:2400.
- [45]. Askary M TalebiSM Amini F and Bangan A D 2017 Effects of ironnanoparticles on *Menthapiperita*L. under salinity stress. *Biologija*63, 65 75.doi:10.6001/biologija.v63i1.3476.
- [46]. Mozafari A Havas F Ghaderi N 2018 Application of iron nanoparticlesand salicylic acid in *invitro* culture of strawberries (*Fragaria× ananassa*Duch.)tocopewithdroughtstress.Plant CellTiss OrganCult132511 523.doi:10.1007/s11240-017-1347-8.
- [47]. MoradbeygiH, Jamei R Heidari R Darvishzadeh R 2020 Investigating the enzymatic and non-enzymatic antioxidant defense by applying iron oxide nanoparticles in *Dracocephalum moldavica* L. plant under salinity stress. *Scientia Horticulturae*. 272109537.
- [48]. Almutairi ZM 2016 Influence of silver nanoparticles on the salt stress resistance of tomato (*'Solanum lycopersicum'* L.) during germination. *Int J Agric Biol* 18 449 457 doi:10.17957/IJAB/15.0114 [GoogleScholar][Cross Ref].
- [49]. Zhou T Prasher S Qi Z George S Mawof A Nzediegwu C Dhiman J Patel R 2021 Impacts of silver nanoparticles in waste water on Heavy metal Transport in soil and uptake by Radish plants. *Water Air Soil Pollut* 232 267. doi: 10.1007/S 11270-02105227-8. [GoogleScholar][Cross Ref].
- [50]. Khalil I Yehye WA Etxeberria AE Alhadi AA Dezfooli SM Julkapli NBM Basirum WJSeyfoddinA 2020 Nanoantioxidants: Recent trends in antioxidant delivery application. *Antioxidants* 9 24 doi:10.3390/antiox9010024.[Google Scholar][Cross Ref].
- [51]. Mohammadi R Maali Amiri R Abbasi A 2013 Effect of TiO₂ nanoparticles on chickpea response to cold stress. *Biolo. Trac e Elem. Res.* 152, 403–410. doi:10.1007/s12011-013-9631-x.
- [52]. Almutairi ZM 2016 Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (*'Solanum lycopersicum'* L.) seedlings under salt stress. *Plant Omics*. 9 106.
- [53]. Adrees M Khan Z Ali S Hafeez M Khalid S Ur Rehman M Z 2020 Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. *Chemosphere* 238:124681. doi:10.1016/j.chemosphere. 124681.
- [54]. Pereira, AES 2019 Potential Use of Polymeric Particles for the Regulation of Plant Growth. In: Gutiérrez, T. (eds) *Polymers for Agri-Food Applications*. Springer, Cham https://doi.org/10.1007/978-030-19416-1_4.
- [55]. - Samreen T Rasool S Kanwal S Riaz S Muntaha S TNazir MZ 2022 Role of Nanotechnology in Precision Agriculture. *Environ. Sci Proc* 23 17. <https://doi.org/10.3390/environsciproc2022023017>.
- [56]. Mishra Singh B R Singh A Keswani C Naqvi AH Singh HB 2014 Biofabricated silver nanoparticles act as a strong fungicide against *Bipolaris sorokiniana* causing spot blotch disease in wheat. *PLoS ONE* 9:e97881.
- [57]. Tarafdar J CXiong Y Wang WN Quinl D Biswas P 2012 Standardization of size, shape and concentration of nanoparticle for plant application. *Appl Biol Res* 14 138 144.
- [58]. Chhipa H 2017 Nanofertilizers and nanopesticides for agriculture. *Environ Chem Lett* 15 15 22. doi:10.1007/s10311-016-0600-4.
- [59]. Delfani M Baradarn Firouzabadi M Farrokhi N Makarian H 2014 Some physiological responses of black eyed pea to iron and magnesium nanofertilizers. *Commun. Soil Sci. Plant Anal.* 45, 530–540. doi:10.1080/00103624.2013.863911.
- [60]. Liu X Zhang F Zhang S He X Wang R Fei Z 2005 Responses of peanut to nano-calcium carbonate. *Plant Nutri Ferti Sci.* 11 385 389.
- [61]. Liu Lal R 2015 Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (*Glycine max*). *Sci Rep* 4:5686. doi:10.1038/srep05686.
- [62]. Dhoke S K Mahajan P Kamble R Khanna A 2013 Effect of nanoparticles suspension on the growth of mung (*Vigna radiata*) seedlings by foliar spray method. *Nanotechnol Dev* 3:e1. doi: 10.4081/nd.2013.e1.
- [63]. Subbaiah LV Prasad TN VK V Krishna TG Sudhakar P Reddy BR Pradeep T 2016 Novel effects of nanoparticulate delivery of zinc on growth, productivity, and zinc biofortification in maize (*Zeamays* L.). *J Agricul Food Chem* 64 3778 3788. doi: 10.1021/acs.jafc.6b00838.
- [64]. Liu R Zhang H Lal R 2016 Effects of stabilized nanoparticles of copper, zinc, manganese, and iron oxides in low concentrations on lettuce (*Lactuca sativa*) seed germination: nanotoxicants or nanonutrients? *Water Air Soil Poll* 227 242. doi: 10.1007/s11270-015-2738-2.
- [65]. Ghafariyan M H Malakouti M J Dadpour M R Stroeve P Mahmoudi M 2013 Effects of magnetite nanoparticles on soybean chlorophyll. *Environ Sci Technol* 47 10645 10652. doi: 10.1021/es402249b.
- [66]. Giannousi K Avramidis I Dendrinos-Samara C 2013 Synthesis, characterization and evaluation of copper based nanoparticles as agrochemicals against Phytophthora infestans. *RSC Adv* 2013;3:21743–21752. doi: 10.1039/c3ra42118j. [CrossRef] [Google Scholar].
- [67]. Kumar SV Rajpriya A Vidhya E Nilavukkarasi Punitha VN 2023 Agriculture Revolution Impact on a Modest Dosage of Silver Nano-Fertilizer: A Green Strategy. *Chemistry Africa* 6 3059 3066 <https://doi.org/10.1007/s42250-023-00692-6>