Nanotechnology for Biotic and Abiotic Stress Management and Soil Health

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Abstract— *Nanotechnology has emerged as a revolutionary approach in agriculture, offering innovative solutions for managing biotic and abiotic stresses while simultaneously promoting soil health. Plants are constantly exposed to a variety of biotic (living) and abiotic (non-living) stresses in their environment. Biotic stresses, primarily caused by pathogens such as bacteria, fungi, viruses, and pests, pose substantial challenges to global food security. Nanotechnology offers precise tools for disease management through the development of nanoherbicides, nanofungicides and nanoemulsions. Abiotic stresses, including drought, salinity, heavy metals, and extreme temperatures, exert detrimental effects on crop productivity. Nanomaterials, such as nanosensors and nanofertilizers, play a pivotal role in alleviating these stressors by improving nutrient and water use efficiency. Nanosensors facilitate real-time monitoring of environmental conditions, allowing for precise and timely interventions. Nanofertilizers, on the other hand, enable controlled nutrient release, reducing wastage and minimizing adverse environmental impacts. Nanotechnology guarantees site-specific delivery of nutrients to the specific region within the plant, minimizing losses and enhancing effectiveness. The smaller dimensions of nanomaterials provide a larger surface area for pesticides and fertilizers, increase their bioavailability, significantly improve disease and pest management in crops, and effectively address the limitations associated with conventional pesticide application. Also, the creation of nano enzymes has transformed the way plants manage stress, as they function as highly effective antioxidant enzymes. These nano enzymes have gained significant traction in combating salinity tolerance in recent times. For instance, cerium oxide nanoparticles (nanoceria) coated with polyacrylic have demonstrated efficient elimination of hydroxyl radicals. In addition to stress management, nanotechnology also contributes to enhancing soil health. Nanoparticles and nanocomposites improve soil structure, water retention, and nutrient availability. Furthermore, the enhanced mobility of nutrients in nanoscale formulations minimizes leaching and runoff, reducing the risk of water pollution. Nanotechnology represents a promising paradigm in agriculture for managing biotic and abiotic stresses, enhancing soil health, and ensuring sustainable crop production.*

Keywords— Nanotechnology in agriculture, Biotic stress management, Abiotic stress management, Soil health, Nanofertilizers, Nanosensors, Nanopesticides, Nanoherbicides, Nanozymes, Nanomaterials.

I. INTRODUCTION

As per the National Nanotechnology Initiative (NNI), nanotechnology involves the understanding, engineering, and practical application of materials on a nanoscale, typically ranging from 1 to 10 nanometres in size. The concept of "nanobiotechnology" was initially coined by biophysicist Lynn W. Jelinski at Cornell University in the United States. Nanoparticles (NPs) have a considerably high surface energy and an elevated surface-to-volume ratio, factors that boost their reactivity and biochemical activity. Nanotechnology presents a unique opportunity to pioneer novel tools and technologies for the investigation and manipulation of biological systems. Its expansive reach extends across various domains and offers a broad spectrum of applications, particularly within the realms of biotechnology and the agricultural sector.

Plants, being immobile organisms, continuously confront environmental fluctuations and various stressors, either individually or in combination, throughout their lifespan. Despite this, plants have evolved diverse mechanisms to combat unfavourable conditions. Remarkably, the way they respond can exhibit significant variations, even among members of the same plant species. The biotic and abiotic stresses are significant constraints that have a detrimental impact on crop productivity and the growth of plants. In the current scenario, agriculture confronts its most significant challenges, including pests, climate change, and a reduction in the availability of essential nutrients. Worldwide, approximately 22,000 various plant pathogens, weeds, insects, and mites exert their influence on farming (Zhang *et al.*, 2021). Not all crop plants possess inherent resistance genes against pathogenic diseases, making their need for external support more critical compared to genetically modified crops. Micronutrients such as copper (Cu), manganese (Mn), and zinc (Zn) play essential roles in initiating enzyme activities and generating biomolecules that contribute to plant defense mechanisms. Consequently, the pursuit of a more sustainable alternative remains one of the most formidable challenges in agriculture, intending to enhance crop production and effectively manage plants against diseases and pest attacks. (Adisa *et al*., 2019). The utilization of engineered nanomaterials (ENMs) has garnered significant attention in the context of both plant stress management and the improvement of soil fertility. It has emerged as a powerful tool in agriculture, offering innovative solutions to address biotic and abiotic stress in crops while promoting soil health. In this chapter, we will explore the applications of nanotechnology in managing these stresses and improving soil quality. We will delve into the mechanisms involved, the latest advancements, and the potential challenges and ethical considerations.

The application of fertilizers in agriculture is a common practice aimed at increasing productivity to meet the growing demand for food. Fertilizers play a crucial role in supporting crop growth, development, and production. However, a significant portion of applied fertilizers often goes unused by plants due to various factors such as leaching in soil and degradation by processes like photolysis, hydrolysis, and decomposition. Despite the necessity of fertilizers for agriculture, managing their application and ensuring efficient utilization remains a challenge for farmers and agricultural experts (Singh *et al.*, 2016). The application of nanofertilizers emerges as a promising alternative to enhance resource use efficiency in agriculture while addressing the issue of increased soil toxicity associated with the accumulation of chemical fertilizers and pesticides. Nanofertilizers, characterized by their nano-sized particles, offer improved nutrient delivery and increased plant absorption, resulting in enhanced crop yields. Unlike traditional chemical fertilizers, nanofertilizers may mitigate the problem of unutilized nutrients, as their nanoscale properties can enhance nutrient availability for plants. Furthermore, the use of nanofertilizers has the potential to alleviate soil toxicity concerns by minimizing the accumulation of conventional fertilizers in the soil. This innovative approach could contribute to sustainable agriculture by optimizing nutrient utilization, reducing environmental impacts, and promoting soil health (DeRosa *et al.,* 2010 and Nair *et al*., 2010).

II. BIOTIC STRESS IN PLANTS

Biotic stress results from interactions with living organisms, such as pests, pathogens, and herbivores. These stressors can have devastating effects on plant health and crop yield:

1) **Pests:** Insects, mites, and other herbivores feed on plant tissues, causing damage by consuming leaves, stems, and roots. They can also transmit diseases, further compromising plant health.

2) **Pathogens:** Bacteria, fungi, viruses, and other microorganisms can infect plants, leading to diseases that weaken or kill them. Plant pathogens can spread rapidly and devastate entire crops if not managed effectively.

3) **Weeds:** Although not usually considered pests, invasive plants (weeds) compete with cultivated crops for resources, including water, nutrients, and sunlight, leading to reduced crop productivity.

III. ABIOTIC STRESS IN PLANTS

Abiotic stressors are non-living environmental factors that can adversely affect plant growth and development. Common abiotic stressors include:

1) **Drought:** Insufficient water availability can lead to reduced turgor pressure, stomatal closure, and impaired photosynthesis, resulting in wilting and decreased growth.

2) **Salinity:** High soil salt concentrations can disrupt water uptake by plants, leading to osmotic stress and ion toxicity. Salt-affected soils are challenging for agriculture.

3) **Temperature Extremes:** Extreme cold or heat can disrupt cellular processes and damage plant tissues. Frost can be harmful to sensitive crops.

4) **Nutrient Deficiency/Toxicity:** Imbalances in essential nutrients can lead to nutrient deficiencies or toxicities, affecting plant health and yield.

5) **Heavy Metals:** Contaminated soils with heavy metals like lead, cadmium, and mercury can accumulate in plant tissues, posing a threat to both plants and consumers.

Among abiotic stresses, factors such as drought, salinity, alkalinity, submergence, and mineral toxicity/deficiencies are recognized as significant contributors to decreased crop growth and productivity. Among these abiotic stresses, salinity, drought, and low temperature are identified as the primary factors leading to substantial reductions in crop yield. Plants respond to abiotic stress through various adaptive mechanisms. These include altering their physiological processes, adjusting root architecture, and accumulating compatible solutes to maintain cellular osmotic balance. Additionally, some plants exhibit stress tolerance through genetic adaptations, which can be exploited in breeding programs.

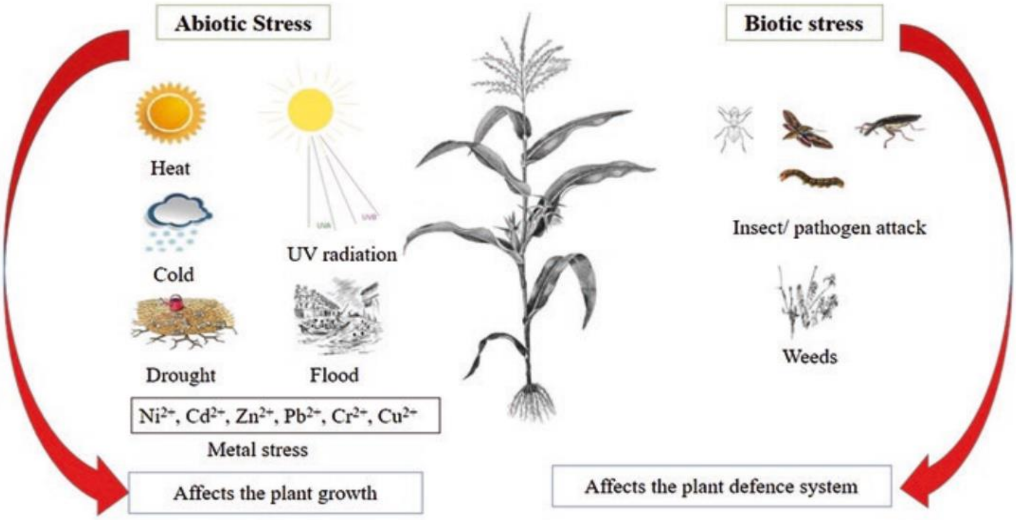

FIGURE 1: Various abiotic and biotic stress factors impact the growth and defense mechanisms of plants.

IV. MECHANISMS

Under abiotic stress conditions, various reactive oxygen species (ROS) are generated, including hydrogen peroxide (H_2O_2), hydroxyl radical (OH^-), superoxides (O_2^-), singlet oxygen species ($1O_2$), and hydroperoxy radical (HO_2). These reactive oxygen species (ROS) instigate harmful effect to cells and genes (Shen *et al*., 2010) and trigger a series of cell signalling events and influencing the activation or inhibition of numerous gene expressions for defense mechanisms.

TABLE 1
KEY ENZYMATIC AND NON-ENZYMATIC ANTIOXIDANTS INVOLVED IN PLANT ROS SCAVENGING UNDER ABIOTIC STRESS

Enzymatic antioxidants	Superoxide dismutase (SOD)
	Catalase (CAT)
	Ascorbate peroxidase (APX
	Glutathione reductase (GR)
Non-enzymatic antioxidants	Glutathione
	Ascorabate

V. NANOPARTICLES IN BIOTIC AND ABIOTIC STRESS MANAGEMENT:

The synthesis of nanoparticles can be achieved through various methods, including physical, chemical, and biological approaches. While chemical synthesis has been a predominant method, there is a growing emphasis on biological synthesis, often referred to as green synthesis, using plants or their extracts. Plants, regardless of being herbs, shrubs, or trees, contain a variety of compounds such as enzymes, sugars, proteins, and phytochemicals like flavonoids, latex, phenolics, terpenoids, alcohols, amines, and cofactors. These compounds play a crucial role as reducing and stabilizing agents during the synthesis of metallic nanoparticles from metal salts. The utilization of plant-based materials in nanoparticle synthesis is considered an eco-friendly approach, offering controlled synthesis with a well-defined size and shape. This not only provides a sustainable solution but also helps prevent atmospheric pollution, making it a promising avenue for the development of nanoparticles with diverse applications (Kumar *et al*., 2009; Sharma *et al*., 2009; Siddiqui *et al*., 2014). Numerous studies have highlighted that the impact of nanoparticles on plant growth and development is concentration-dependent. The concentration of nanoparticles applied can influence the nature and extent of their effects on plants. Interestingly, nanoparticles have been found to upregulate the activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). These antioxidant enzymes play a crucial role in mitigating oxidative stress and maintaining cellular homeostasis. The concentration-dependent responses suggest that careful consideration and optimization of nanoparticle concentrations are essential in harnessing their beneficial effects on plant growth while minimizing potential adverse effects. This nuanced understanding is critical for the successful integration of nanoparticles in agricultural practices to enhance crop performance sustainably Laware *et al*., 2014)

Silicon nanoparticles: Silicon (Si) is abundantly present in the soil and Earth's crust, playing a crucial role in plant defense and growth. Silicon nanoparticles have gained attention for their ability to effectively disperse over a wide area. For example, it is estimated that 1.0 gram of silica nanoparticles with a diameter of 7.0 nm can provide a wide absorption surface equal to 400 m^2. Additionally, silica nanoparticles influence xylem humidity, water translocation, and enhance turgor pressure in plants. This results in increased leaf relative water content and water use efficiency, ultimately contributing to improved plant health and productivity. (Wang *et al*., 1994; Rawson *et al.*, 1988). Studies have shown that silica nanoparticles (SNPs) can enhance plant growth and yield, particularly under stress conditions. This improved tolerance may be attributed to the absorption of silicon nanoparticles by plant roots. Once absorbed, SNPs can develop a fine layer within the plant cell wall, providing structural support that helps plants resist various stresses. By reinforcing the cell wall, SNPs assist in maintaining plant yield even when faced with environmental challenges such as drought, salinity, or disease. This mechanism highlights the potential of silica nanoparticles as a valuable tool for enhancing crop resilience and productivity in agricultural settings (DeRosa *et al*., 2010).

Zinc oxide nanoparticles: Micronutrient fertilizers have been shown to enhance plant tolerance to environmental stresses such as drought and salinity. Zinc (Zn) is one such important micronutrient necessary for the optimal growth and development of plants. It facilitates vital metabolic reactions within plants, promoting their growth and development. In addition to its primary role in plant growth, zinc also plays a crucial role in reducing the uptake of toxic heavy metals by plants. This function helps protect plants from heavy metal toxicity, such as cadmium (Cd), by limiting their absorption from the soil. By providing adequate zinc through fertilization, growers can not only support healthy plant growth but also mitigate the risks associated with heavy metal contamination in agricultural environments (Baybordi*et al*., 2005). Zinc oxide (ZnO) nanoparticles have been found to have a stimulating effect on the auxin (indole-3-acetic acid, IAA) levels in plant roots or sprouts. Auxins are crucial plant hormones responsible for promoting and regulating various aspects of plant growth and development, including cell elongation, root development, and overall plant architecture. The increased auxin levels induced by ZnO nanoparticles contribute to the promotion of plant growth. This suggests that ZnO nanoparticles can potentially serve as a growth-promoting agent by modulating hormone levels in plants, providing an avenue for optimizing plant development in agricultural and horticultural practices.

Titanium dioxide nanoparticles: Titanium dioxide (TiO_2) nanoparticles exhibit photocatalytic properties, initiating oxidation-reduction reactions that generate superoxide anion radicals and hydroxides when exposed to light. Interestingly, despite this inherent photocatalytic nature, photosterilization by TiO_2 nanoparticles has been found to positively impact plant growth and development. Studies have indicated that TiO_2 nanoparticles, particularly in the rutile phase, enhance antioxidant stress tolerance in plants. This is achieved by modulating various processes, including reducing the accumulation of superoxide radicals, hydrogen peroxide, malonyldialdehyde (MDA) content, and inducing the activities of antioxidant enzymes within plants. Enzymes such as superoxide dismutase, catalase, ascorbate peroxidase, and guaiacol peroxidase are influenced by the photochemical reactions occurring in the chloroplasts of plants like Spinacia oleracea. The findings suggest that TiO_2 nanoparticles can play a role in enhancing plant stress tolerance and antioxidant defense mechanisms (Lei, 2010).

VI. BIO-PRIMING FOR ALLEVIATING BIOTIC AND ABIOTIC STRESS

Bio-priming serves as a highly efficient means of administering biocontrol agents, with priming being recognized as an optimal approach for triggering resistance mechanisms. This method enhances the effectiveness of rhizobacteria-induced resistance in plants. Trichoderma harzianum is extensively utilized for bio-priming due to its broad spectrum of antagonistic activity against various plant pathogens, particularly fungi and nematodes(Singh *et al*., 2005).Symbiotic fungi, specifically vesicular-arbuscular mycorrhiza (VAM), including species such as *Acaulospora* sp., *Ambispora* sp., *Gigaspora* sp., *Glomus* sp., *Pacispora*sp., and *Paraglomus*sp., have demonstrated significant effects on plant nutrient absorption, growth, and an impressive ability to withstand abiotic stress, particularly during drought conditions (Oliveira *et al*., 2006).

Several mechanisms have been proposed for the microbial-induced enhancement of abiotic stress tolerance in plants. Symbiotic stress tolerance in plants involves two key mechanisms: firstly, the activation of host stress response systems immediately upon exposure to stress, enabling plants to avoid or mitigate stress impacts (Schulz *et al.*,1999); secondly, the biosynthesis of anti-stress biochemicals by endophytes (Miller *et al*., 2002; Schulz *et al*., 2002). The manifestation of this biosynthesis leads to various mechanisms, such as osmotic adjustment, which imparts tolerance to abiotic stresses. Osmotic adjustments, achieved through an enhanced production of osmolytes, result in increased water retention within cells, thereby improving the water use efficiency of the plant. The higher concentration of osmolytes in plant cells contributes to increased cell wall elasticity and an elevated turgid weight to dry weight ratio (TW/DW). Endophytes play a role in synthesizing alkaloids such as lolines, which provide osmotic protection by reducing stomatal conductance and alleviating drought stress (Morse *et al.*, 2002). These alkaloids serve to protect macromolecules from denaturation and/or reactive oxygen species (ROS) associated with drought stress (Schardl *et al*., 2004).

VII. NANOPESTICIDE IN BIOTIC STRESS MANAGEMENT

Nanopesticides, formulated by encapsulating conventional pesticides within nanoparticles, represent a breakthrough in pest management. They offer several advantages, such as controlled release, reduced environmental impact, and enhanced efficacy. Nanopesticides minimize off-target effects, making them environmentally friendly. Furthermore, they can be designed to release pesticides in response to specific triggers, like pH or temperature, ensuring targeted pest control. Silver nanoparticles, for instance, have exhibited excellent antimicrobial properties against various plant pathogens, while carbon-based nanoparticles can serve as carriers for pesticide delivery.

VIII. NANOENCAPSULATION OF BIOCONTROL AGENTS

Nanoencapsulation also extends to beneficial microorganisms used in biological control. Encapsulating biocontrol agents within nanoparticles protects them from harsh environmental conditions, improves their stability, and enhances their colonization on plant surfaces. This approach fosters a more sustainable and eco-friendly means of managing plant diseases and pests.

Nanoencapsulation involves the encapsulation of biocontrol agents, such as beneficial microorganisms or natural compounds, within nano-sized particles. This technique offers several advantages for the delivery of biocontrol agents in agriculture. Firstly, nanoencapsulation protects the biocontrol agents from environmental degradation, such as UV radiation or enzymatic degradation, prolonging their shelf life and viability. Additionally, nanoencapsulation enables the controlled release of the biocontrol agents, ensuring a sustained and targeted delivery to the desired site of action, such as the rhizosphere or phyllosphere of plants. This enhances the efficacy of biocontrol agents in suppressing plant pathogens or pests while minimizing off-target effects. Moreover, nanoencapsulation can improve the stability and solubility of biocontrol agents, enhancing their compatibility with agricultural formulations and facilitating their application through various delivery systems, including foliar sprays, seed treatments, or soil drenches. Overall, nanoencapsulation holds great potential for enhancing the efficacy, stability, and delivery of biocontrol agents in integrated pest management strategies, contributing to sustainable and environmentally-friendly agricultural practices.

IX. NANOTECHNOLOGY FOR ABIOTIC STRESS MANAGEMENT

9.1 Nanosensors for Environmental Monitoring:

Nanosensors play a pivotal role in assessing soil conditions and responding to abiotic stressors. These tiny devices can detect variations in soil moisture, salinity, and nutrient levels at high precision. Farmers can receive real-time data, enabling them to make informed decisions about irrigation and nutrient application, which is vital in drought-prone regions. Nanosensors can also detect heavy metal contamination in soil, allowing for early intervention to prevent soil degradation. Nanosensors offer a powerful tool for real-time monitoring of stress factors in crops, enabling timely interventions and precise management strategies as follows:

1) **Early Detection:** Nanosensors can detect subtle changes in plant physiology, such as alterations in hormone levels, chlorophyll fluorescence, or reactive oxygen species production, which serve as early indicators of stress. Early detection allows farmers to take proactive measures to mitigate stress before visible symptoms appear.

2) **Environmental Monitoring:** Nanosensors can measure various environmental parameters, including temperature, humidity, light intensity, and soil moisture content, which influence plant stress levels. By continuously monitoring these factors, nanosensors provide valuable insights into the environmental conditions affecting crop health and productivity.

3) **Nutrient Status Monitoring:** Nanosensors can measure nutrient levels in soil and plant tissues, providing real-time information on nutrient availability and uptake efficiency. This enables precise fertilizer application tailored to the specific needs of crops, reducing nutrient waste and minimizing environmental impacts.

4) **Water Stress Monitoring:** Nanosensors can detect changes in soil moisture levels and plant water status, enabling accurate assessment of water stress in crops. This information allows for optimized irrigation scheduling and efficient water management practices, conserving water resources and improving crop resilience to drought.

5) **Disease and Pest Detection:** Nanosensors can identify the presence of pathogens, pests, and their associated biomolecules in crops, facilitating early detection of diseases and pest infestations. Early detection enables timely implementation of control measures, such as targeted pesticide application or quarantine procedures, to prevent yield losses.

6) **Stress Response Monitoring:** Nanosensors can monitor plant responses to stress at the molecular level, including the expression of stress-related genes, synthesis of stress-responsive proteins, and accumulation of stress-induced metabolites. This information provides insights into the mechanisms underlying plant stress tolerance and informs breeding efforts to develop stress-resistant crop varieties.

7) **Data Integration and Analysis:** Nanosensors generate large amounts of data that can be integrated with other agricultural data sources, such as remote sensing imagery, weather forecasts, and agronomic databases. Advanced data analytics techniques, including machine learning and predictive modelling, can process this data to identify patterns, predict stress events, and optimize management decisions.

By providing real-time, site-specific information on crop stress factors, nanosensors enable precision agriculture practices that optimize resource use, minimize input costs, and maximize crop yields while promoting environmental sustainability. Continued research and development in nanosensor technology are essential to enhance sensor performance, scalability, and affordability for widespread adoption in agriculture.

9.2 Nanoparticles for Soil Remediation:

Contaminated soils are a global concern, with heavy metals being one of the most common pollutants. Nanoparticles like zero-valent iron (nZVI) have shown remarkable potential for remediating heavy metal-contaminated soils. These nanoparticles can immobilize or transform toxic heavy metals into less harmful forms, restoring soil health. Additionally, nanomaterials can enhance nutrient availability by increasing nutrient retention and slow release, reducing the need for excessive fertilization.

9.3 Carbon nanotubes:

Carbon nanotubes (CNTs) have emerged as promising tools for mitigating abiotic stresses in crops due to their unique physicochemical properties and versatile applications. The mechanism underlying the role of CNTs in abiotic stress management involves several key factors. Firstly, CNTs possess high surface area and exceptional mechanical strength, which enable them to serve as carriers for various biologically active compounds such as antioxidants, Osmo protectants, and growth-promoting substances. These compounds can help alleviate abiotic stress-induced damage by scavenging reactive oxygen species (ROS), stabilizing cell membranes, and regulating osmotic balance in plants.

Moreover, CNTs exhibit excellent electrical conductivity and thermal stability, allowing them to act as nanoscale electrodes for enhancing electron transfer processes in plants. This facilitates the activation of stress-responsive signalling pathways and the induction of stress tolerance mechanisms, such as the synthesis of stress-related proteins and the accumulation of compatible solutes. CNTs possess the ability to interact with soil particles and improve soil structure, porosity, and water retention capacity. This creates a conducive microenvironment for root growth and microbial activity, facilitating nutrient cycling and enhancing soil fertility. The multifaceted mechanisms of CNTs in abiotic stress management involve their roles as carriers for biologically active compounds, enhancers of electron transfer processes, facilitators of nutrient and water uptake, improvers of soil properties, and sensors for stress monitoring.

X. NANOTECHNOLOGY AND SOIL HEALTH

- Soil Nutrient Management: Nano-fertilizers, with their tailored nutrient release profiles, improve nutrient use efficiency. They ensure that plants receive essential nutrients precisely when needed, minimizing nutrient leaching and environmental pollution.
- Soil Microbial Activity: Nanotechnology also influences soil microbial communities positively. Nanostructures act as carriers for beneficial microorganisms, protect them from environmental stressors, and enhance their proliferation. This supports nutrient cycling and overall soil health.
- Soil Structure and Porosity: Nanoparticles can improve soil structure by reducing compaction and enhancing porosity. This leads to better aeration, water infiltration, and root penetration, ultimately improving soil fertility.

XI. CONCLUSION

Nanotechnology holds immense potential for revolutionizing agricultural practices by addressing the complex challenges of biotic and abiotic stresses while promoting soil health and sustainability. Through the development of innovative nanomaterials and nanodevices, researchers and agricultural practitioners can harness the unique properties of nanoparticles to enhance the resilience of crops against pests, diseases, drought, and other environmental stressors. Nanotechnology enables precise and targeted delivery of biocontrol agents, pesticides, and nutrients, thereby minimizing environmental impacts and optimizing resource utilization. Moreover, nanosensors provide real-time monitoring of soil health parameters and crop stress factors, facilitating data-driven decision-making and precision agriculture practices.

Furthermore, nanomaterials such as nano zero-valent iron (nZVI) contribute to soil remediation efforts by degrading pollutants and improving soil fertility, while nano-hydrogels enhance water retention and nutrient availability in soils. Additionally, nanoencapsulation techniques protect and deliver beneficial microorganisms and natural compounds, promoting sustainable pest management strategies. By leveraging the transformative potential of nanotechnology, we can pave the way toward a more resilient, efficient, and sustainable agricultural system for future generations.

REFERENCES

[1] Adisa, I. O., Pullagurala, V. L. R., Peralta-Videa, J. R., Dimkpa, C. O., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2019). Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action. *Environmental Science: Nano*, *6*(7), 2002-2030.

[2] Baybordi, A. (2005). Effect of zinc, iron, manganese and copper on wheat quality under salt stress conditions. *Journal of water and Soil*, *140*, 150-170.

[3] DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., & Sultan, Y. (2010). Nanotechnology in fertilizers. *Nature nanotechnology*, *5*(2), 91-91.

[4] Kumar, V., & Yadav, S. K. (2009). Plant‐mediated synthesis of silver and gold nanoparticles and their applications. *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology*, *84*(2), 151-157.

[5] Laware, S. L., &Raskar, S. (2014). Effect of titanium dioxide nanoparticles on hydrolytic and antioxidant enzymes during seed germination in onion. *Int. J. Curr. Microbiol. App. Sci*, *3*(7), 749-760.

[6] Lei, Z. (2010). Antioxidant stress is promoted by nano-anatase in spinach chloroplasts under UV-Beta radiation. *Biological trace element research*, 121, 69–79.

[7] Miller, J. D., Mackenzie, S., Mark, F. O. T. O., Adams, G. W., & Findlay, J. A. (2002). Needles of white spruce inoculated with rugulosin-producing endophytes contain rugulosin reducing spruce budworm growth rate. *Mycological Research*, *106*(4), 471-479.

[8] Morse, L. J., Day, T. A., & Faeth, S. H. (2002). Effect of Neotyphodium endophyte infection on growth and leaf gas exchange of Arizona fescue under contrasting water availability regimes. *Environmental and Experimental Botany*, *48*(3), 257-268.

[9] Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant science*, *179*(3), 154-163.

[10] Oliveira, L. A., Porto, A. L., &Tambourgi, E. B. (2006). Production of xylanase and protease by Penicillium janthinellum CRC 87M-115 from different agricultural wastes. *Bioresource Technology*, *97*(6), 862-867.

[11] Rawson, H. M., Long, M. J., & Munns, R. (1988). Growth and development in NaCl-treated plants. I. Leaf Na+ and Cl-concentrations do not determine gas exchange of leaf blades in barley. *Functional Plant Biology*, *15*(4), 519-527.

[12] Schardl, C. L., Leuchtmann, A., & Spiering, M. J. (2004). Symbioses of grasses with seedborne fungal endophytes. *Annu. Rev. Plant Biol.*, *55*, 315-340.

[13] Schulz, B., Boyle, C., Draeger, S., Römmert, A. K., & Krohn, K. (2002). Endophytic fungi: a source of novel biologically active secondary metabolites. *Mycological research*, *106*(9), 996-1004.

[14] Schulz, B., Römmert, A. K., Dammann, U., Aust, H. J., & Strack, D. (1999). The endophyte-host interaction: a balanced antagonism. *Mycological Research*, *103*(10), 1275-1283.

[15] Sharma, V. K., Yngard, R. A., & Lin, Y. (2009). Silver nanoparticles: green synthesis and their antimicrobial activities. *Advances in colloid and interface science*, *145*(1-2), 83-96.

[16] Shen, X., Zhou, Y., Duan, L., Li, Z., Eneji, A. E., & Li, J. (2010). Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. *Journal of plant physiology*, *167*(15), 1248-1252.

[17] Siddiqui, M. H., Al-Whaibi, M. H., Faisal, M., & Al Sahli, A. A. (2014). Nano-silicon dioxide mitigates the adverse effects of salt stress on Cucurbita pepo L. *Environmental toxicology and chemistry*, *33*(11), 2429-2437.

[18] Singh, J., & Lee, B. K. (2016). Influence of nano-TiO2 particles on the bioaccumulation of Cd in soybean plants (Glycine max): A possible mechanism for the removal of Cd from the contaminated soil. *Journal of environmental management*, *170*, 88-96.

[19] Singh, U. S., Zaidi, N. W., Joshi, D., Khan, T., John, D., & Bajpai, A. (2005). Trichoderma: a microbe with multifaceted activity. *Annual Review of Plant Pathology (Vol. 3)*, *3*, 33-75.

[20] Wang, J., & Naser, N. (1994). Improved performance of carbon paste amperometric biosensors through the incorporation of fumed silica. *Electroanalysis*, *6*(7), 571-575.

[21] Zhang, X., & Zhang, Y. (2021). Experimental study on enhanced heat transfer and flow performance of magnetic nanofluids under alternating magnetic field. *International Journal of Thermal Sciences*, *164*, 106897.