NANOTECHNOLOGY TO MITIGATE ABIOTIC STRESS IN HORTICULTURE CROPS

Abstract

Horticultural crops have multiple uses, including providing food and aesthetic value. These plants are a significant source of carbohydrates, vitamins, proteins, organic acids, and minerals for human health & nutrition. Abiotic effects, includes drought, flooding, inadequate nutrition levels, heat, light, and metal stress, restrict crop plant growth and output. Tolerance to abiotic stress can be increased through various strategies, such as creating genetically altered cultivars with added genes that enhance their resilience to stress. Nanotechnology is a broad discipline with potential applications in all areas of study, including business, agriculture, and medicine. There needs to be more understanding of the effects of nanoparticle interaction with plants, considering the rapid progress in using nanoparticles in many applications. With an emphasis on modern research, this chapter discusses about the primary role of nanoparticles in horticultural crops under abiotic stress. This chapter additionally defines how various nanoparticles can improve horticultural plants' ability to withstand abiotic stress.

Keywords: Nanotechnology, abiotic, horticultural, nutrition

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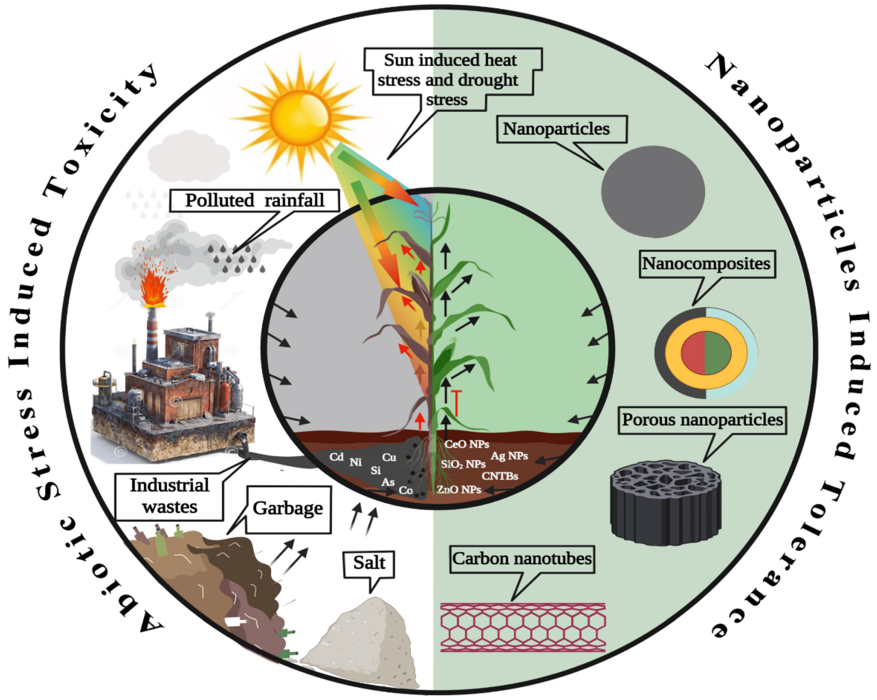
I. INTRODUCTION

Nanotechnology has emerged as a prominent field that has profoundly impacted various aspects of life and initiated a new era of progress. At its core, nanotechnology involves the manipulation of particles at the nanoscale, typically with dimensions smaller than 100 nanometers, which serves as the fundamental building block [1]. This technology enhances productivity while safeguarding against both biotic and abiotic stress factors, offering a fresh perspective on balancing agricultural production and environmental sustainability. By harnessing nanotechnology, we can revolutionize agriculture and the food industry through innovative tools designed to bolster crop stress resistance and enhance nutrient absorption in plants. These tools, including nanoparticles found in nano fertilizers, nano pesticides, and nanosensors for monitoring nutrient levels, hold the potential to boost productivity and shield against biotic and abiotic stressors. Nano fertilizers, for instance, increase crop yield and quality by enhancing nutrient uptake and reducing production costs, thereby contributing to the resilience of agriculture [1]. Nanoparticles are commonly employed as pesticides to combat biotic stress in agriculture, offering a sustainable alternative that minimizes the use of conventional pesticides, resulting in lower environmental impact [2]. Nevertheless, the management of input materials for nanotechnology remains a significant challenge, especially in contrast to industrial nanoproducts, where control over nanomaterials inputs is more established [2]. The application of nanotechnology is currently under exploration in food technology and agriculture, with a focus on reducing the need for traditional plant protection products and boosting crop yields. These applications encompass the use of nanocapsules and nanoparticles for disease detection and treatment. While the potential of nanotechnology in agriculture is substantial, there are still critical issues, such as risk assessment, that must be addressed.

Various types of abiotic stressors pose significant challenges to plant growth and development, impacting their metabolism and overall health. These stresses, which encompass factors like water scarcity, heat, salt, heavy metals, and others, often act in combination, further complicating the situation and leading to reduced plant growth and crop yields [3]. For instance, salt stress, a consequence of soil salinity, severely affects agriculture in regions with water scarcity and inadequate drainage systems, leading to decreased crop productivity [5]. Similarly, drought stress, caused by unequal rainfall distribution due to climate change, poses a significant threat to grain production, with adverse effects on plant growth and development [8]. Heat stress also adversely affects plant growth, particularly when temperatures rise above or fall below the optimum range, impacting crop yields [16]. Furthermore, heavy metals in soil can impair plant metabolic activities and threaten food chains and ecosystems [17].

Nanotechnology offers promising solutions to mitigate the impact of abiotic stress on plants. Nano-stimulators, including natural plant extracts, chemicals, and nano-metals or nanocomposites, have been studied for their potential to assist plants in overcoming stressors [21]. These nanocomposites, fabricated using nanotechnological methods, consist of macronutrients and micronutrients that are designed to improve nutrient uptake by plant roots while reducing nutrient losses to the environment. For example, calcite-based nanofertilizers have been shown to advance the growth stages of grape cultivars and enhance various factors like berry weight, cluster number, and pruning weight [22]. Additionally, the application of zinc oxide nanoparticles has been found to improve soil fertility and promote plant development, as demonstrated in the case of okra [7]. In the face of drought stress, fullerenol nanoparticles have shown promise in acting as intracellular depots for water molecules, potentially benefiting plants [12]. These nanomaterials have the potential to enhance crop production and protect plants from the adverse effects of abiotic stressors. Nanotechnology has shown significant promise in mitigating abiotic stress in horticultural crops, offering innovative solutions to improve crop resilience and productivity in challenging environmental conditions. Here's an elaboration of how nanotechnology can help address various abiotic stresses in horticultural crops:



II. DIFFERENT TYPES OF ABIOTIC STRESS ON PLANTS IS MITIGATED BY NANOPARTICLES

1. **Abiotic Stresses and Crop Plants:** Stress is characterized by stimuli inhibiting plant growth, development, and metabolism under biotic and abiotic conditions [1]. Numerous plant species defend themselves from harmful environmental factors. In most cases, multiple stresses coexist, such as the combined effects of water, heat, salt, heavy metals, and other light stresses. These modifications reduce plant growth, metabolism, and output by interfering with source-sink interactions and regular plant metabolism functions [3]. Additionally, these stresses change how several plant genes express themselves, significantly impacting crop production globally and lowering average yields of significant crops like wheat and rice [4].

2. **Drought Stress:** Drought stress poses a significant challenge in the realm of horticultural crop production, as it can result in diminished plant growth, reduced yields, and compromised fruit quality. Climate change has exacerbated this issue by causing uneven

rainfall distribution, leading to pronounced drought stress. This condition arises from insufficient water availability and cellular dehydration, which in turn causes a decrease in water potential, stomatal closure, and turgor pressure, ultimately impeding plant growth and development [8]. The adverse effects of low water availability extend to various biochemical and physiological functions, including ion acquisition, chlorophyll synthesis, photosynthesis, respiration, and nutrient metabolism. Consequently, plant growth is hampered by such low water stress conditions [9]. Plants respond to low-water stress through a complex process involving physiological and biochemical adjustments within the plant system. During drought conditions, plants curtail their shoot development and metabolic demands. For instance, in maize, a water shortage of approximately 40% can lead to yield reductions of up to 40%, and in wheat, 21% yield reduction is observed [9]. Cowpea, when subjected to drought stress, can experience a substantial yield decline ranging from 34% to 68% [8]. Given the profound impact of climate change on agricultural plant yields, performance, and stability, addressing low water availability becomes pivotal for global food security [10]. Raising environmental awareness and enhancing plant drought tolerance are increasingly critical to sustaining crop quality. To this end, numerous engineered nanomaterials are being explored in agriculture with the aim of enhancing crop productivity and protection [11]. Among these nanomaterials, carbon-based nanomaterials (CBNMs) have garnered significant attention in recent years and have proven beneficial in agriculture and biotechnology [10]. Prominent examples include fullerene derivatives such as C60, C70, and C60(OH)x, where x ranges from 18 to 36, as well as carbon nanotubes (CNTs). In one notable application, fullerene nanoparticles (FNPs) were introduced into various tissues of bitter melon (Momordica charantia) using a seed priming technique, resulting in increased biomass, fruit yield, and phytomedicine content. It has been established that fullerenes have the ability to traverse various cell membranes and compartments [12]. When fullerenol is dissolved in water, it forms polyanion nanoparticles, with their size and charge dependent on experimental conditions such as concentration, pH, temperature, and the presence of co-solvents. These nanoparticles possess the capability to bind water molecules, making them effective intracellular reservoirs during osmotic stress. Through nanotechnology, hydrogel nanoparticles and nanoclays can be created and incorporated into the soil to enhance its water-holding capacity. These nanoparticles can absorb and retain water, forming a reservoir that gradually releases moisture to plant roots. This augmentation of the soil's water retention capacity ensures a consistent and prolonged water supply to crops, enabling plants to maintain sufficient hydration even during arid periods and reducing the severity of drought stress. Certain nanoparticles, such as cerium oxide nanoparticles, function as antioxidants that scavenge reactive oxygen species (ROS) produced under drought stress in Sorghum bicolor (L.) Moench. ROS can inflict damage on plant cells, but antioxidant nanoparticles shield these cells from oxidative stress induced by drought. This safeguarding of plant health prevents cellular damage and allows crops to endure water-scarce periods. When applied as a foliar spray, nanoceria shields sorghum plants from oxidative damage during drought stress, resulting in increased grain yields [25].

3. **Salinity Stress:** Soil salinity presents a significant challenge to agriculture in regions where water scarcity and inadequate drainage systems in irrigated farms significantly reduce crop productivity [5]. Salinity stress, resulting from elevated salt levels in the soil or irrigation water, can have severe adverse effects on the growth and productivity of horticultural crops. Nanotechnology offers innovative solutions to mitigate salinity stress

in these crops by enhancing soil conditions, improving nutrient uptake, and minimizing the detrimental impacts of excessive salt. According to the Food and Agricultural Organization (FAO, 2016) [6], more than 6% of the total global land area and 19.5% of the total irrigated land are already affected by salinity issues. Both human activities and natural factors can contribute to soil salinity. Of the 932.2 million hectares of salt-affected soils worldwide, human-induced factors are responsible for 76.6 million hectares of soil salinization [5]. These salt-affected lands typically contain higher levels of exchangeable sodium and soluble salts, often due to inadequate leaching of cations that form the soil's foundation. The primary soluble salts acting as anions include sulfate (SO2−4SO4−), carbonate (CO2−3CO3−), chloride (Cl−), and nitrate (NO−3NO3−) salts, while the cations involve potassium, calcium, magnesium, and sodium. Hyper-saline soil water also contains various metals, such as selenium, lithium, boron, strontium, silica, fluorine, rubidium, manganese, aluminum, and molybdenum, some of which can be detrimental to animals, humans, and plant health. Salt accumulation in plants can impede their growth and reduce their capacity to absorb nutrients and water, resulting in osmotic stress. Zinc oxide, often referred to as ZnO, is a valuable material known for its non-toxic nature, photocatalytic properties, affordability, and long-term stability. Zinc oxide nanoparticles (ZnO-NPs) offer numerous advantages for soil fertility, plant production, and serving as a zinc source, an essential micronutrient for enhancing plant growth and protection, particularly in crops like Okra [7]. Okra is a widely cultivated vegetable crop in many regions around the world. The application of ZnO nanoparticles in Okra plants is aimed at mitigating salt stress, thereby improving their overall resilience and productivity.

4. **Heat Stress:** Plants are vulnerable to heat stress, with the potential for plant mortality occurring at extremely high temperatures. Typically, plants exhibit optimal performance within a specific temperature range, and deviations from this range, whether below or above it, can have a profoundly negative impact on plant growth and development [16]. Most biochemical and enzymatic reactions show a doubling of their rate between temperatures of 20°C to 30°C, with variations in this range across different regions. Temperatures exceeding or falling below this range result in reduced reaction rates due to enzyme denaturation or inactivation, respectively. Even slight temperature fluctuations of one or two degrees can significantly affect plant growth and development, particularly during the critical early stages of male gametophyte formation in various crops like wheat, rice, sorghum, barley, maize, and chickpea [16]. Heat stress can lead to male sterility and abnormalities in spikelet production in rice and wheat [11]. In wheat and rice, both cold and heat stress can lead to tapetum breakdown, alterations in the callose walls of microspores, changes in exine formation, and shifts in carbohydrate metabolism, ultimately resulting in male sterility. Notably, temperature stress does not adversely affect female gametophyte development [11]. One potential solution to mitigate heat stress involves the use of titanium dioxide nanoparticles as protective coatings applied to plant leaves. These coatings serve to reflect sunlight and reduce heat stress by helping to maintain lower leaf temperatures, thus preventing damage caused by excessive heat [26].

5. **Heavy Metals Stress:** Metal poisoning stands out as a prominent environmental hazard that hinders the normal metabolic functions and activities of plants. Heavy metals (HMs) represent a class of inorganic substances that are persistent and non-biodegradable, characterized by an atomic weight exceeding 20 and a density greater than 5 g cm−3. These substances have far-reaching effects, causing contamination in food chains,

irrigation systems, soils, aquifers, and the surrounding atmosphere, ultimately leading to mutagenic, cytotoxic, and genotoxic consequences for human, plant, and animal health [17]. The excessive use of fertilizers and the expansion of industrialization contribute to the accumulation of toxic metals in agricultural soils, resulting in adverse repercussions for the interaction between soil and plants [18]. These toxic metals accumulate slowly in the plant system through water and air, eventually entering the food chains over time, posing a significant threat to the natural food web and biogeochemical cycles [19]. The unprecedented accumulation and bioaccumulation of heavy metals in the environment present a challenge for all forms of plant and organism life. Elevated concentrations of HMs can interact with various vital cellular components, including nucleoproteins and DNA, leading to the excessive production of reactive oxygen species (ROS) and subsequent profound changes in plants, such as proteolysis, shoot chlorosis, and lipid peroxidation [19]. In response to abiotic stressors, nanotechnology offers inventive solutions for alleviating heavy metal stress in horticultural crops by focusing on the remediation of contaminated soils and reducing the uptake of toxic heavy metals by plants. Strategies include the use of osmolytes, nanoparticles, mineral nutrients, hydrogels, antioxidants, protectants, potassium, and plant growth hormones like uniconazole and salicylic acid to enhance plant productivity [20]. Additionally, plants can adapt to the adverse impacts of drought by utilizing plant hormones such as brassinolide (BR), gibberellic acid (GA), auxins, ABA, cytokinins, JA, and ethylene, which regulate numerous beneficial responses in plants [20]. Nano-sized materials like nanoclays, nano-oxides (e.g., iron oxide nanoparticles), and nano-zerovalent iron offer promising solutions for remediating heavy metal-contaminated soils. These nanoparticles possess extensive surface areas and reactivity, allowing them to adsorb, immobilize, or transform heavy metals into less toxic forms. They can be incorporated into the soil to reduce the bioavailability of heavy metals to plant roots.

6. **Nutrient Stress:** Nanofertilizers: Nano-sized nutrient formulations can improve the efficiency of nutrient delivery to plant roots, ensuring that horticultural crops receive the necessary nutrients for optimal growth and development.

7. **Oxygen Stress:**Nanoparticle Oxygen Carriers: Nanoparticles loaded with oxygen molecules can serve as carriers to deliver oxygen directly to plant roots in waterlogged or oxygen-deprived soils. This can prevent root suffocation and promote healthier root systems.

8. **UV Radiation Stress:** UV-Blocking Nanoparticles: Nanoparticles, such as zinc oxide or titanium dioxide, can be incorporated into agricultural films, coatings, or sprays to block harmful UV radiation. This protects plants from UV-induced damage and sunburn.

9. **Cold Stress :** Inadequate or irregular water supply, often the result of water stress, can exert a significant impact on the growth, development, and yield of horticultural crops. Nanotechnology provides a range of approaches to alleviate water stress in these crops by enhancing water availability, improving water use efficiency, and mitigating the consequences of water scarcity. This type of stress is recognized as the primary abiotic stressor responsible for reducing agricultural crop productivity, leading to decreased crop quality and postharvest longevity. Cold stress encompasses both chilling, occurring

between 0–15 °C, and freezing conditions at 0 °C, both of which can have adverse effects on plant growth and agricultural production [13]. When comparing the impact of freezing and chilling stress, it becomes evident that freezing stress is considerably more detrimental to plants. Typically, the harmful effects of freezing stress initiate with the formation of ice nucleation within plant cells, followed by the progressive growth of ice crystals, leading to water leakage and cell dehydration [14]. Several major crops, including tomato (Solanum lycopersicum), maize (Zea mays), rice (Oryza sativa), cotton (Gossypium hirsutum), and soybean (Glycine max), lack the ability to acclimate to cold conditions and can only thrive in tropical and subtropical regions [15]. Consequently, cold stress detrimentally impacts plant growth, metabolism, and development, resulting in reduced crop yields on a global scale [14]. Some nanoparticles possess antifreeze properties and can be applied to plants as a protective measure against freeze or chill stress, effectively preventing the formation of ice crystals within plant tissues.

10. **Mechanical Stress:** Mechanical stress in horticultural crops can result from various factors such as wind, heavy rainfall, or mechanical handling during farming operations. Nanotechnology can offer innovative solutions to reduce mechanical stress in these crops. Here's how nanotechnology can be applied to mitigate mechanical stress. Strengthened cell walls make plant tissues more resistant to mechanical damage from wind or rain, reducing the likelihood of broken branches or stem damage.

III. IMPACT OF NANOPARTICLES ON PLANT RESISTANCE TO ABIOTIC STRESS

Stress in plants results from a combination of biotic and abiotic factors that hinder their growth, development, and metabolic regulation. Various plant species have evolved defense mechanisms against adverse environmental conditions. Often, these protective responses initiate late, leading to irreversible damage. Therefore, it becomes necessary to employ stimulants to support plant growth in agricultural systems. Recent research has explored the use of nano-stimulants, encompassing chemicals, natural plant extracts, or combinations thereof, along with the potential use of nano-metals and nanocomposites [21]. One promising approach in nanotechnology involves the development of nanocomposites, which consist of macronutrients (N, P, and K) and micronutrients derived from biomaterials. This innovation helps prevent undesired nutrient losses to the soil, water, and atmosphere. For example, calcium carbonate ($CaCO3$) comprises 40% silicon dioxide ($SiO2$), 4% magnesium oxide (MgO), and 1% iron(III) oxide ($Fe2O3$). When applied at a rate of 0.5 g in calcareous orchards, the Narince grape cultivar exhibited accelerated development in three key stages: full bloom, véraison, and maturity. Under alkaline stress conditions, the application of this compound resulted in an advancement of four days in véraison and maturity dates compared to untreated control vines (véraison: 30.07 in control versus 26.07 in NF treatment; maturity: 29.08 in control versus 25.08 in NF treatment). Additionally, parameters such as berry weight (NF treatment: 234.7 g; control: 223.6 g), cluster weight (NF treatment: 341.9 g; control: 310.8 g), cluster number (NF treatment: 17.6; control: 16.3), and pruning weight (NF treatment: 547.4 g; control: 505.4 g) exhibited notable differences from the control [22]. Pruning weight holds particular importance in determining vine vegetative growth and variations in vine canopy size due to vineyard management practices [23].

The beneficial effects of zinc (Zn) on plant physiology, particularly its influence on tryptophan synthesis (a precursor to indole-3-acetic acid, IAA), contribute to improved pollen production, berry development, and cluster unification in grapevines. This may explain the observed increases in berry weight, cluster number and weight, and pruning weight following the application of Zn-containing nano-stimulants (NFs) [24]. Any factor capable of elevating endogenous Zn levels in plants, such as NF application, can enhance IAA synthesis, thereby promoting the growth of shoots, berries, and pollen while reducing the incidence of underdeveloped shoot berries.

Furthermore, studies have shown that spraying strawberry plants with selenium nanoparticles (Se-NPs) at concentrations of 10 and 20 mg L-1 enhances their tolerance to salinity and increases yield. This effect is attributed to the ability of Se-NPs to safeguard photosynthetic pigments, resulting in a 12.19% increase in chlorophyll a and a 40.47% increase in chlorophyll b content, along with a 13.63% increase in free proline levels compared to non-NP-treated plants. Similarly, applying Se-NPs (1 and 2 M) to pomegranate plants mitigates fruit cracking caused by drought stress, with the 2 M concentration (4.0%) outperforming the 1 M concentration (7.2%) compared to the non-NF treatment.

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