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The Significance of Nanoparticles in Plant Tolerance to Abiotic Stress in Horticulture Crops: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Not only are horticultural crops necessary for human sustenance, but they also enhance the aesthetic appeal of our surroundings. They provide a wealth of essential nutrients in addition to visual attractiveness. However, abiotic factors such as heat, drought, nutrient deficits, and heavy metal stress pose several obstacles to these crops, severely impeding their development and output. Many approaches have been used to address these issues, such as genetic alterations to increase stress resistance. Several industry applications, including agricultural ones. Nanotechnology offers novel solutions in the field of agriculture, including the remediation of soil and water, plant protection at the nanoscale, and the application of nano-nutrition to crops. In order to ensure sustained success in horticulture crops that face a range of environmental problems, these applications are essential. Nevertheless, there is still much to learn about the specific ways in which nanoparticles interact with plants, even in spite of the fact that their use in a wide range of applications is growing. This offers agriculture a successful and sustainable future.

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1. INTRODUCTION

Abiotic stressors, which include salt, drought, heavy metals (HMs), and water logging, are the main factors that restrict plant development and agricultural yield globally. In response to these kinds of challenges, plants activate a number of complex systems that change the morpho-physiological and biochemical processes. In recent decades, traditional breeding, genetic engineering, and marker-assisted breeding have all been used to address abiotic stressors in plants. As technology advances, effective solutions to the negative impacts of abiotic environmental restrictions are needed to create crop production systems that are sustainable in agriculture [1] By enhancing plant resilience to abiotic stress, NPs may boost crop yields in sustainable agriculture and solve both current and future production issues. Exogenously applied chemicals are one of several effective and environmentally friendly methods that have been used to lessen the negative effects of abiotic stress on plants and improve their capacity to adapt to unfavourable circumstances [2].

2. ABIOTIC STRESSES

Plants encounter a wide range of challenges throughout their life cycles, broadly categorized as biotic stresses caused by living organisms like bacteria, viruses, and nematodes, and abiotic stresses resulting from environmental factors. Abiotic stress, particularly, is a major concern that has a significant impact on the productivity and quality of horticultural crops. These stressors, which encompass soil salinity, flooding, and extreme temperatures (both high and low), disrupt various stages of crop growth and development [3]. They divert their energy away from growth and reproduction to adapt to the stress, ultimately leading to reduced crop yields [4]. In fact, unfavorable conditions can slash crop yields by as much as 70% [5]. These ROS can inflict damage on lipids, proteins, and DNA, leading to cellular harm and even plant death [6]. To counteract the excessive production of ROS and the associated oxidative stress, plants have developed an effective antioxidative defense system. This system comprises both enzymatic and non-enzymatic components. Besides generating which serve as osmolytes to maintain cellular stability [7]. The combined impact of these stresses, including interactions between biotic and abiotic factors. This is a pressing concern for horticultural crops, which not only have higher market value but also require more resources and provide essential nutrients in our diets. A significant portion of the essential vitamins and minerals we need comes from vegetables and fruits, and a deficiency in these can lead to nutritional diseases and, in severe cases, even death [8]. Abiotic stresses don't just decrease crop yields; they also affect the quality of the produce, leading to changes in appearance and nutritional value [9]. Often involving changes in gene expression [10]. However, these adaptive strategies come at a cost, diverting energy and nutrients away from normal growth processes. These practices include selecting appropriate cultivars, timing planting, adjusting planting density, and optimizing water and fertilizer use [11]. Additionally, strategies such as protected cultivation, soilless farming, and grafting are used to protect plants from adverse conditions. Grafting, in particular, is a crucial method for maintaining the resistance of vegetable crops, especially high-yield varieties like cucurbits and solanaceous plants. It enhances their ability to withstand challenges like saline soil, nutrient or water deficiencies, and the harmful effects of heavy metals or pollutants [12]. Genetic improvement stands out as another pathway to bolster crop tolerance to abiotic stresses by transferring genes associated with stress responses. Scientists have placed particular emphasis on regulatory genes, such as transcription factors, which have the ability to govern multiple stress-related genes simultaneously. Nevertheless, genetic improvement encounters challenge due to the intricate nature of plant responses, genetic diversity, and the protracted breeding process [13]. In vitro selection emerges as a valuable tool for developing stress-tolerant plant lines, especially with regard to salt and drought tolerance. This method involves inducing genetic variation in plant cells, exposing them to stressors, and subsequently regenerating the entire plant from the surviving cells. While this approach is less time-consuming and costly than traditional genetic engineering, it does have its limitations concerning trait stability and potential epigenetic changes [14]. In summary, abiotic stresses represent a substantial threat to agriculture, especially for high-value horticultural crops. Dealing with these challenges requires a multifaceted approach, which includes a combination of agronomic practices, genetic enhancement, in vitro selection, and the creative utilization of biostimulants and bioactive compounds to guarantee both crop yield and quality [15].

3. INTRODUCTION TO NANOPARTICLES

Nanotechnology is a field that focuses on the manipulation of matter, whether it's living or non-living, at incredibly small scales, involving individual atoms and molecules [16]. Its applications have gained significant recognition, to the extent [17]. Within the field of nanotechnology, structures and devices measuring less than 100 nanometers are modified in at least one dimension to produce nanomaterials with distinctive characteristics. These nanomaterials are tailored for use across various industries [18]. Nanotechnology encompasses the processing, synthesis, manipulation, and utilization of nanomaterials, typically measuring 100 nanometers or less in size. These materials exhibit remarkable optical characteristics, size-dependent properties, and a significant surface area, making them highly valuable for applications in areas like nutrition and plant protection [19]. In agriculture, the incorporation of nanoparticles into crops has demonstrated its effectiveness. This practice bolsters plant growth, development, quality, and yield, while also enhancing the plants' ability to withstand unfavorable environmental conditions. Furthermore, it's worth noting that, in certain conditions, plants themselves can naturally produce nanomaterials. The field of nanotechnology holds the promise of offering farmers and consumers environmentally friendly and health-conscious options, ultimately driving economic growth without adverse impacts on the environment and human well-being [20].

4. TRANSLOCATION AND UPTAKE OF NANOPARTICLES IN PLANTS

Various techniques are commonly employed to introduce nanoparticles (NPs) into plants, including methods like seed coating, soil saturation, and foliar spray applications. Given the pivotal role of plants in the soil ecosystem, they serve as a potential pathway for NPs to be taken up, transported, and integrated into the food chain [21]. It's crucial to comprehend how plants absorb NPs. A previous study conducted by Zhu, Han, Xiao, & Jin in 2008 demonstrated that FeO NPs could be absorbed, transported, and accumulated in pumpkin plants without causing harm. A noteworthy finding was that a substantial portion of the accumulated iron content, specifically 67.4%, was detected within the root tissues, with 45.4% distributed both internally and externally across the root surface. In contrast, only a minute fraction, just 0.6%, was identified within the leaf tissue. Moreover, copper oxide nanoparticles were found to exhibit mobility within maize plants through the xylem and phloem conduits, as reported by Wang in 2012. Additionally, research conducted by Lin et al. in 2009 revealed the capability of Fullerene (C70) nanoparticles to traverse the vascular system of rice plants, potentially being passed on to subsequent generations.

The apoplastic and symplastic routes are the two different paths by which nanoparticles (NPs) enter plant roots and leaves and then migrate throughout the plant [22]. In 2020, Cui et al. conducted a different investigation in which they discovered SiO2 NPs in rice cells contaminated with arsenic. After first passing through the cell walls, these NPs disseminate throughout the interstitial spaces between cell walls and plasma membranes, according to advanced imaging methods. Their continued movement may be influenced by capillary forces and osmotic pressure [23]. Although there are a number of possible methods for NPs to enter plant cells, including ion channels, carrier proteins, and aquaporins, the specific processes are still unclear [24].

5. IMPACTS OF NANOPARTICLES ON PLANTS EXPERIENCING HEAVY METAL STRESS

Including atmospheric deposition, industrialization, waste disposal, and industrial processes [25]. The persistent presence of heavy metals (HMs) in polluted soils gives rise to significant environmental concerns. This situation has far-reaching consequences, affecting not only plants but also posing threats to humans and animals through exposure to harmful compounds [26]. The accumulation of these substances in plants can result in oxidative damage, disrupt photosynthesis, disturb ion regulation, and hinder nutrient absorption, ultimately impeding plant growth [27].

Researchers have been actively investigating the potential of nanoparticles (NPs) in addressing the challenges posed by heavy metal (HM)-contaminated soil, with recent studies demonstrating promising outcomes [28]. For example, FeO NPs have shown their ability to mitigate the harmful effects of cadmium (Cd) toxicity in wheat plants, leading to enhanced plant growth, increased chlorophyll levels, and improved antioxidant enzyme activity. NPs have proven effective in curbing the accumulation of toxic ions within plant cells, thereby shielding them from the stress resulting from excessive ions. Furthermore, the beneficial effects of silicon (Si) NPs in counteracting phytotoxicity induced by HMs have been observed [29]. These findings underscore the significance of further research in the development of innovative nano-remediation strategies, effectively combatting the detrimental effects of HMs on plant growth and development.

6. THE IMPACT OF NANOPARTICLES ON PLANTS EXPERIENCING DROUGHT STRESS

Drought stands as a prominent environmental challenge that has garnered considerable attention from both environmental and agricultural experts. It presents a substantial threat to global agriculture, significantly impeding plant growth and diminishing crop yields. Drought stress impacts various facets of plant development, ultimately jeopardizing the economic viability of the agricultural sector [30]. Drought stress is marked by the scarcity of moisture, leading to reduced cell size, cell membrane damage, the initiation of oxidative stress, and premature leaf aging. All these factors contribute to a decline in crop yield [31].

For example, hawthorn plants exhibited increased resilience to drought when treated with Si NPs [32]. Similarly, Si NPs have played a significant role in aiding the recovery of barley plants following drought stress, exerting their influence on a range of morphophysiological traits [33]. Chitosan NPs have also proven advantageous by enhancing relative water content, the rate of photosynthesis, and the activities of catalase (CAT) and superoxide dismutase (SOD) [34].

7. THE INFLUENCE OF NANOPARTICLES ON PLANTS FACING SALT STRESS

Soil salinity represents a prominent global issue that exerts a substantial impact on crop yields. It introduces ionic toxicity and disrupts the ionic balance within plants [35]. Consequently, sodium (Na^+) and chloride (Cl^-) ions accumulate within plant cells, causing toxicity that severely impairs plant health [36]. Salt stress leads to a significant depletion of potassium ions (K^+) in leaf mesophyll cells, while the concentration of sodium ions (Na^+) within the cell's cytosols rises. This disrupts the plant's ability to assimilate carbon dioxide (CO_2) in saline environments. The reduction in CO_2 assimilation directly impacts crop growth rates and overall production [37]. Manganese NPs, employed for seed priming, have proven effective in managing salinity stress by influencing molecular responses in pepper crops [38].

8. CONCLUSION

The study emphasises how essential horticulture crops are to satisfying our aesthetic and nutritional needs. However, a variety of abiotic stresses pose significant difficulties to these crops, calling for creative solutions to improve their production and resilience. The rapidly developing science of nanotechnology offers prospective agricultural solutions in areas like as nutrition, protection of nanoscale plants, and cleanup of soil and water. Although regulations have been put in place to guarantee the appropriate use of nanoparticles, there is still a lack of information on how these particles interact with plants. It is clear from the future that nanomaterials have a great deal of promise for horticulture crops to reduce abiotic stress. It is crucial to conduct ongoing study on the precise functions and effects of nanoparticles in plant interactions. This study might improve our knowledge of how to use nanotechnology to support crops in an efficient manner. The research highlights how crucial horticultural crops are to meeting our dietary and aesthetic requirements. But a range of abiotic stressors provide serious challenges for these crops, necessitating innovative approaches to boost resilience and productivity. Potential agricultural solutions in areas like nutrition, protecting nanoscale plants, and cleaning up land and water are provided by the rapidly advancing science of nanotechnology. Despite the implementation of rules aimed at ensuring the proper use of nanoparticles, little is known about the interactions that these particles have with plants. Future research makes it abundantly evident that nanomaterials have enormous potential for horticultural crops in terms of lowering abiotic stress. Research on the specific roles and impacts of nanoparticles in plant interactions must continue. This research might have a major impact on agriculture's sustainability by expanding our understanding of the ways in which nanotechnology can be used to increase crop resistance to environmental stresses. resistance in the face of environmental difficulties, significantly improving agriculture's sustainability.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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