



Nanomaterials for Crop Stress Mitigation

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Crop production worldwide is under severe threat from abiotic stresses like drought, salinity, extreme temperatures, and heavy metal toxicity and biotic stresses like pathogens and pests attack, which collectively reduce yields and threaten global food security. Conventional approaches depend upon chemical fertilizers and pesticides are increasingly insufficient, with nitrogen use efficiency below 40% in most cropping systems, resulting in significant environmental losses. Nanotechnology has emerged as a transformative solution by harnessing materials at a scale of 1-100 nanometer (nm), in which unique surface reactivity and enhanced delivery mechanisms make them exceptionally effective in agricultural systems. Nanomaterials include zinc oxide (ZnO), silicon (SiNPs), titanium dioxide (TiO₂), and chitosan nanoparticles improve nutrient use efficiency, activate antioxidant enzyme systems, regulate osmotic balance, and protect photosynthetic machinery under stress.

Keywords: Nanomaterials, Crop stress, Abiotic stress, Nutrient use efficiency, Antioxidant enzymes, Sustainable agriculture

Introduction

Weeds, pests, diseases and abiotic stresses are the major constraints in agricultural production worldwide. In India, where over 60% of cultivated land is rainfed and majority face soil salinity and micronutrient deficiencies, the drop in what farmers earn and food security is high. Conventional responses i.e. heavier fertilizer doses, repeated pesticide applications, and expanding irrigation are reaching their ecological and economic limits, with nitrogen use efficiency in most cropping systems remaining below 40. Nanotechnology is the science of manipulating materials at scale of 1–100 nm which offers a fundamentally different path. At this scale, materials acquire extraordinary properties like high surface-area-to-volume ratios, enhanced reactivity, and the ability to interact directly with plant cellular machinery. It is a new opportunity in plant sciences and that opportunity is now being systematically realized through nanomaterials designed to enhance crop resilience, nutrient efficiency, and stress tolerance.

How Nanomaterials Protect Crops

The best-studied process is the up-regulation of antioxidant enzyme systems in plants. Siddiqi and Husen (2017) reviewed that at low, non-toxic concentrations, engineered nanomaterials can effectively upregulate the antioxidant defense system, enhancing the activity of enzymes such as Superoxide Dismutase (SOD), Catalase (CAT), and Peroxidase (POD). The latter three enzymes play key roles in eliminating ROS. CeO₂ nanoparticles deserve special attention because they can use Ce³⁺/Ce⁴⁺ to perform functions similar to those of antioxidants, constantly removing ROS without undergoing any consumption themselves. Silicon nanoparticles (SiNPs) were found to reduce arsenate (AsV) toxicity more effectively than bulk silicon, mainly due to their higher bioavailability to seedlings (Tripathi et al. 2016).

Beyond this antioxidant activation, nanomaterials also protect and enhance photosynthesis under stress. Titanium dioxide nanoparticles were shown to promote growth and ameliorate salinity stress effects in *Dracocephalum moldavica* by enhancing photosynthetic pigment content and antioxidant enzyme activity (Gohari et al. 2020). The role of SiNPs is to increase the strength of cell walls using a process called silicification. This reduces water loss via transpiration by 15-20%. On the other hand, ZnO nanoparticles inhibit the breakdown of chlorophyll molecules and ensure light absorption capability during drought and heat. During salinity and drought conditions, nanomaterials help osmotic adjustment, which includes the production of proline by SiNPs, activation of Na⁺/H⁺ antiporter (SOS pathway) by ZnO nanoparticles to keep sodium ions out of the cytoplasm, and regulation of aquaporin by TiO₂ nanoparticles.

Nano fertilizers probably constitute one of the most commercially successful uses of nanotechnology in agriculture. High surface area, ability to provide sustained slow release, and capability to diffuse into leaves via stomata without going through soil fixation reactions result in increased nitrogen fertilizer efficiency two to three times higher compared to traditional urea fertilizers. Zulfiquar et al. (2019) reported that nanofertilizers improve nutrient uptake while minimizing the environmental pollution typically caused by conventional fertilizers. While nanofertilizers are promoted as a means to improve nutrient delivery and reduce environmental losses, Kah et al. (2018) cautioned that such benefits are not consistently demonstrated across studies and that nano-enabled products may pose novel environmental risks.

Agronomic Applications

Rastogi et al. (2017) described how ZnO and Fe₂O₃ nanoparticles may improve crop performance through enhanced photosynthesis, nutrition, and stress tolerance, although effects vary by species and application rate. Nanoparticles can be delivered via foliar spray, seed priming, or soil application, with dosage and efficacy varying by nanoparticle type and crop species. Biodegradable chitosan nanoparticles that leave no residue have been found to stimulate Systemic Acquired Resistance, thereby destroying the membranes of fungal cells via electrostatic attraction and resulting in a reduction in diseases in vegetable and ornamental crops. Hill farming in areas such as Himachal Pradesh, which have acidic soil (pH ranging from 4.5-5.5), unpredictable monsoon rains, and tiny terrace fields, is likely to benefit from the use of nanotechnology-based formulations as foliar sprays to reduce fertilizer use by 25-30%.

Limitations and Future Prospects

Despite their immense potential, the use of nanomaterials in agriculture should be based on sound science. The difference between effective and harmful doses of nanoparticles is minimal and depends on the type of plants, with excessive amounts leading to decreased seed germination, chlorosis, and suppression of enzyme activity. Field conditions may differ significantly from laboratory studies, depending on temperature, soil acidity, organic matter levels, and other factors affecting nanoparticle performance. It should also be noted that the optimal approach to utilizing nanotechnology in agricultural practices includes its integration with traditional fertilization methods, since replacing soil-applied nitrogen with Nano Urea via foliar application leads to a decrease in grain yield in key cereals. Long-term field research on the impact of nanoparticles on soil ecosystems is limited at present, but worldwide legislation in this area continues to change and develop. Future trends in nanoparticle use will likely include developing stimuli-responsive nanoparticles capable of delivering the desired payload upon reaching an environmental trigger, such as a pathogen, soil acidity, or temperature changes, as well as nano-biosensors for real-time crop monitoring.

Conclusion

Nanomaterials is a scientifically sound and advancing technology that offers a physiological and molecular level response to stress alleviation for crops. Through their antioxidant action, increased nutrient uptake efficiency by a factor of two or three, protection of the photosynthetic apparatus, and regulation of genes involved in stress response, nanomaterials like ZnO nanoparticles, SiNPs, TiO₂ nanoparticles, and chitosan nanoparticles can provide multiple mechanisms of action to alleviate the different types of abiotic and biotic stresses affecting our crop production on the planet. The availability of commercially available products like Nano Urea and Nano DAP indicates the success of nano agriculture technology from the lab bench to practical application in agriculture fields. Scientifically responsible implementation requires dose optimization and crop calibration, as well as long-term environmental monitoring.

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