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Exploring the regulatory potential of zinc oxide nanoparticles for alleviating abiotic stress in crop plants

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Abstract

Abiotic stress possess significant challenge against crop development by subjecting them to adverse environmental conditions. Nanoparticles aids as a promising tool for enhancing plant health and improving capacity to tolerate against both biotic and abiotic hindrances. Among the nanoparticles, zinc oxide nanoparticles has been testified to exhibit significant potential in mitigating stress in plants with Zinc as integral micronutrient for diverse physiological mechanisms. ZnO nanoparticles have been studied as a vital component for plant development, including mineral uptake, physiological mechanisms and antioxidant activity. Along with its signifance to plant growth, ZnO nanoparticles also possess advantageous properties such as low toxicity, cost-effectiveness, and compatibility with living organisms, distinguishing them from other types of metal oxide nanoparticles. However, along with its beneficial approach, its application in higher concentrations and prolonged exposure causes adverse consequences on plants. This review focusses to explore current findings of the potential of ZnO nanoparticles in modulating crops development and their potential in mitigating abiotic stressors.

Keywords: nanoparticles, zinc oxide, alleviation, abiotic stress

Introduction

Global agricultural production faces substantial challenges due to abiotic impacts like drought, metal toxicity, temperature effects, salinity and variations in light intensity. These stresses can lead to the generation of toxic compounds such as reactive oxide radicals, which, if not competently detoxified, can negatively impact soil quality, fertility, and various cellular processes crucial for crop growth and developement. To mitigate the detrimental effects of abiotic stresses and enhance plant adaptation, researchers have explored numerous agricultural and physiological strategies (Abd El-Ghany *et al*., 2021). In the realm of agriculture, nanotechnology has gained attention to be a vital strategy in addressing various challenges and promoting sustainable farming practices. It has emerged to be an innovative solution with potential benefits for mitigation of stress for sustainable improved crop development (Seleiman *et al*. 2021b).

Nanotechnology is a captivating and speedily expanding field of study that has led to a number of novelties (El-Saadony *et al*., 2020). In agronomy, nanotechnology has been primarily employed in the development of nanofertilizers and nanopesticides, allowing precise control of nutrient levels, promoting growth, increasing yield, and enhancing stress resilience in crops (Shang *et al*., 2019; Bhatt *et al*., 2020) [6]. The unique physicochemical properties of nanoparticles have led to their considerable significance in molecular investigations. These include their small size ranging from 1 to 100 nanometres, expansive surface area, heightened reactivity, and exceptional stability even in minute concentration (Sanzari *et al*., 2019). Nanoparticles (NPs) thereby emerges as a vital component in regulating plant growth and development even at low concentrations. Their utilization can stimulate the management of plant stress by boosting radical detoxification capabilities and improving antioxidant enzyme acitivity. These effects significantly contribute in controlling the physiological, biochemical, and metabolic activities in plants (Kumari *et al*., 2022) [24]. Notably, NPs is demonstrated to exert a crucial influence on plant stress responses, primarily by up regulating to tolerance genes. (Manzoor *et al*., 2022) [30]. The unique physical, optical, and antibacterial features of zinc oxide nanoparticles (ZnO NPs) have captured considerable interest in scientific investigations. These unique properties have made ZnO NPs a subject of particular interest among the wide range of nanoparticle available (Sabir *et al*., 2014) [39]. ZnO NPs offers a diverse array of uses and advantages over other metal oxide NPs, including lower toxicity, affordability, and biocompatibility. The significant compatibility of ZnO NPs with existing pharmaceutical compounds also further enhances their potential for diverse applications in agriculture (Sahdev *et al*., 2013).

Zinc oxide nanoparticles and its properties

Zinc oxide (ZnO) is a white, powdery odourless inorganic substance nearly insoluble in water (Bacaksiz *et al*., 2008) [5]. In the recent days, ZnO has Zinc oxide (ZnO) has garnered significant interest due to its distinctive properties, abundant availability, and potential benefits with wide range of applications. It has been reported to possess varieties of properties such as enhanced reactivity with its small size and shape, optically active with wide bandgap, biomedical imaging, semiconducting behavior, photocatalytic activity, magnetic nano properties, antimicrobial properties, and drug delivery (Chaari and Matoussi, 2012) [8]. The Food and Drug Administration has designated ZnO as a substance that is "generally recognized as safe (GRAS)" and applied as additive in food (Wang *et al*., 2005). It has also been employed as sensors, energy producers, and catalysts because of their piezo- and pyroelectric characteristics (Wang *et al*., 2005; Wang *et al*., 2008).

ZnO NPs have garnered considerable attention due to their remarkable physical, optical, and antibacterial properties (Sabir *et al*., 2014) [39]. ZnO NPs offers remarkable usages and advantages over other metal oxide NPs, including lower toxicity, affordability, and biocompatibility. Their compatibility with existing pharmaceutical compounds further enhances their potential for diverse applications in agriculture (Sahdev *et al*., 2013). Furthermore, these characteristics make them promising for various applications in the biomedicine and ceramics industry and. They possess desirable traits such as firmness, hardness, targeting ability, biocompatibility, low toxicity and biodegradability (Ozgur *et al*., 2005). Moreover, research has indicated that ZnO nanoparticles (NPs) exhibit bactericidal effects against pathogenic bacteria (Molina *et al*., 2006) [32].

But it is to be noted that ZnO though considered safe for topical use, the safety and potential toxicity of zinc oxide nanoparticles in biological systems are still areas of active research. Careful consideration and evaluation of the specific nanoparticles and their interactions with biological systems are essential for their safe and effective utilization in biological applications (Table 1).

Utilization of ZnO NPs in alleviating plant abiotic stress

Diverse applications of ZnO NPs in mitigating abiotic effects in plants have been recorded. Several studies mention its potential usage in alleviating abiotic stress by functions such as enhanced water retention, hormonal regulation, antioxidant activity, homeostasis and heavy metal toxicity alleviation. In general, the capacity to regulate plant physiology and enhance plant yield and growth appears to be present in ZnO nanoparticles (NPs). The effectiveness of ZnO NPs is primarily influenced by two main factors: the size and dosage of the NPs, as well as the specific type of plants being considered (Khodakovskaya *et al*., 2009) [23] (Fig. 1; Table 1).

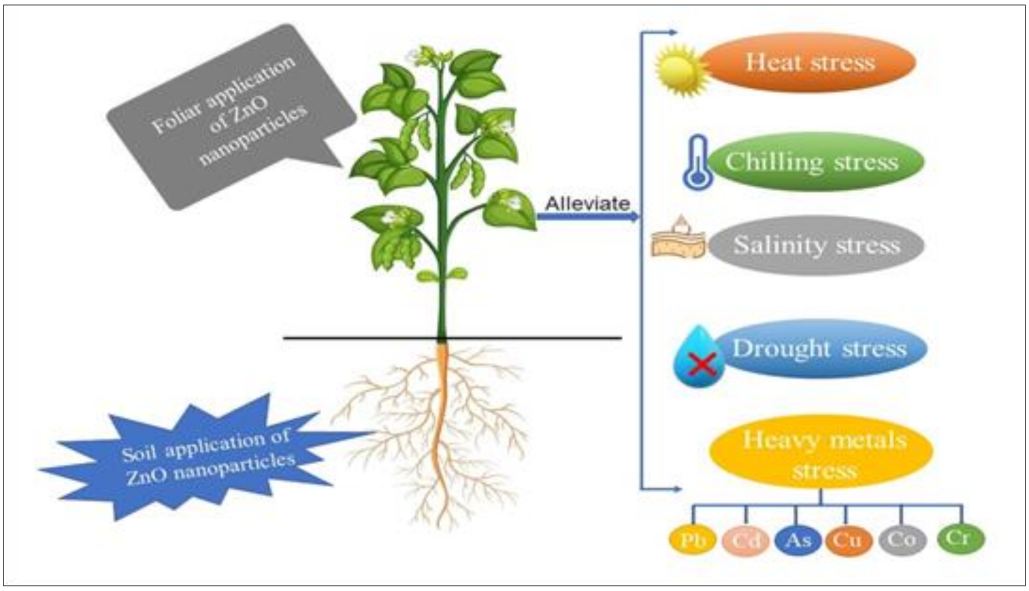

Fig 1: Effects of zinc oxide nanoparticles in regulation of plant abiotic stresses

a. ZnO nanoparticles in drought stress

Drought, a prominent environmental factor, imposes constraints on plant growth and development, leading to adverse consequences for global agricultural productivity. (Tanveer *et al*., 2019). Global warming, alteration in precipitation patterns, and restricted availability of underground water are key factors contributing to drought conditions. The physio-biochemical processes including osmoprotectants accumulation, a decline in accumulation of metabolite content, and the generation of ROS are mainly triggered by drought (Afshari *et al*., 2021) [2].

ZnO NPs have been studied to explore their potential in alleviating the impacts of drought stress in plants (Srivastava *et al*., 2021) [43]. It possess the ability to aggregate and form structures that enhance water retention in the soil which thereby helps to create a microenvironment around plant roots with improved water availability and balanced water level in plants. It also helps to maintain balanced enzymatic functions/ regulations. Occurrence of ZnO NPs not only provide stability to plants but also enhance embryogenesis, and seedling regeneration, thus can reduce biotic impact (Helaly *et al*., 2014) [16]. Dimikpa *et al*. (2019), found that ZnO NPs demonstrated the ability to rectify drought-induced stress in sorghum plants and enhance the water deficit tolerance of eggplants grown in saline soil. Karim *et al*. (2012) [18] also found that Zn spraying has no observable outcome on wheat yield grain when a crop is well under water. However, under drought conditions, it increased grain yield and grain size.

According to a study by Abd El-Aziz *et al*. (2022) [4], it has been found that antiparticles of zinc (Zn) also have an impact on the chlorophyll content of leaves. The study observed that Zn nanoparticles (Zn-NPs) have the ability to increase the chlorophyll levels in leaves, both in the absence of any stress and during periods of drought stress. Importantly, the researchers noted that Zn-NPs are more effective in this regard compared to natural zinc.

ZnO also influenced the enzymatic activities in crops. Studies conducted by Taran *et al*. (2017) [45] and Panda *et al*. (2017) demonstrated that display of diverse levels of ZnO NPs resulted in increased antioxidant enzymatic process in wheat and rice crops. This indicates that ZnO NPs can potentially enhance the antioxidant defense system in crops, providing protection against oxidative stress. Along with enzymatic and photosynthetic activity, they also help enhance nutrient uptake and plant nutrient level (Awad *et al*., 2021). Thus, implementation of ZnO NPs to regulate drought stress may increase quality of crops and maintain its growth and development.

b. ZnO nanoparticles in arsenic stress

Arsenic (As), a potentially toxic metalloid is caused by anthropogenic, including extreme use of chemicals, coal burning, and the preservation of timber (Sharma, 2013). Arsenic in plant cells changes normal cellular metabolic processes predominantly by modifying enzyme functions, affecting the metabolism of carbon and sulfur and the assimilation of nitrogen (Finnegan *et al*., 2012) [13]. Higher levels of arsenic cause the plant to lose its ability to balance between toxicity and resistance, ultimately resulting in loss of plants (Stoeva *et al*., 2005) [44].

During As stress, the use of ZnO NPs to improve photosynthesis activity, significantly raised the chlorophyll content, and also positively regulated the gas exchange characteristics (Faizan *et al*., 2018) [12]. ZnO NPs appear to upregulate the proline and glycine betaine biosynthesis pathways, which may be crucial in reducing As stress (Ahmad *et al*., 2020). In rice, ZnO adsorbs As before it enters into the rice plants due to its powerful adsorption ability, thus improving the antioxidant mechanism (Singh *et al*., 2013).

c. ZnO nanoparticles in cadmium stress

Cadmium (Cd), a heavy metal is carcinogenic to humans. Cd is absorbed and translocated to different regions of plants and it is regarded as an antimetabolite that impairs several physiochemical processes in plants by inactivating enzymes associated with those pathways (Hayat *et al*., 2012) [15]. ROS such as H_2O_2, MDA, and O_2^- are generated by excessive Cd resulting in oxidative stress (Perez-Chaca *et al*. 2014;).

Zn^{2+}, a vital element for plant developement is provided by ZnO NPs. The harmful effects of Cd can be countered by applying ZnO NP (Rizwan *et al*. 2016). ZnO NP accelerates Zn absorption and reduces Cd uptake by plants, thus boosting ionic interconversion ability, promoting nitrogen uptake, and resulting in increased protein content (Sun *et al*. 2005; Hasan *et al*. 2008 [14]; Garg and Kaur 2013; Lawre and Raskar 2014). Ali *et al*. (2015) reported that in the presence of metal stress, ZnO NPs alleviated oxidative stress in *Leucaena leucocephala* plants. ZnO NPs treatment improved the antioxidant defense system by upregulating gene expression involved in various oxidative processes and inhabiting MDA, H_2O_2, and O_2^- levels, thus decelerating lipid peroxidation (Nair *et al*., 2014) [33]. ZnO NPs are shown to promote plant height, no. of leaves, dry biomass of shoots and roots, the concentration of chlorophyll, and gas exchange characteristics. All of the improvements elevated the antioxidant enzyme activity while reducing electrolyte release, MDA, and H_2O_2 levels (Rizwan *et al*., 2019) [22].

d. ZnO nanoparticles in chilling stress

Chilling stress exerts a detrimental impact on the physiological and metabolic processes of rice. Chilling stress inhibits the chlorophyll biosynthesis of rice leaves, and also triggers the accumulation of ROS, MDA, and proline (Yang *et al*., 2013;).

By spraying ZnO NPs, the total chlorophyll accumulation was restored, and chlorosis symptom in rice leaves was greatly reduced (Song *et al*., 2021) [42]. The application of ZnO NPs resulted the increase in expression level of gene associated with the anti-oxidative system and the adverse effect in leaves subjected to chilling stress. The up-regulated genes includes *OsPRX11, OsCu/ZnSOD, OsCATA, OsPRX89, OsPRX65, OsCATB*, as well as transcription factors like *OsMYB, OsNAC5, OsWRKY94, OsWRKY76, and OsbZIP52.* (Song *et al*., 2021).

e. ZnO nanoparticles in salinity stress

The presence of soil salinity has a global influence on reducing crop production (Parida *et al*., 2005) [35]. Salt stress significantly interferes with the physiological metabolism of plants, impeding their growth, development, and ultimately leading to decreased productivity. The major critical consequence of salt stress includes the alteration of thylakoid membrane structure, which adversely affects the efficiency of photosynthetic activity (Singh *et al*., 2018).

ZnO nanoparticles has been reported to improve nutrient and water transportation while reducing water loss. This property of ZnO-NPs is beneficial in promoting water intake under NaCl stress conditions. Furthermore, ZnO-NPs possess the capacity to increase antioxidant levels and improve nutrient uptake. These effects are particularly important for the development of a robust root system, which plays a pivotal role in the growth and resilience of plants under challenging NaCl stress conditions (Singh *et al*., 2023).

Table 1: Significant impacts of ZnO nanoparticles in crop plants under various abiotic stress conditions

Sl.no.	Stress	Plant Studied	Dose of ZnO NP	Comments	Reference
1	Drought	*Triticum aestivum* (Wheat)	–	Increases drought resistance by enhancing antioxidant enzyme activities (SOD and CAT)	Taran *et al*. 2017 [45]
2	Drought	*Triticum aestivum* (Wheat)	100 mg/L	Improves grain and shoot, wheat yield, increases chlorophyll levels and proline antioxidants, uptake of nutrients	Abd El-Aziz *et al*. 2022 [4]
3	Drought	*Coriandrum sativum* L.	100 ppm	Improves net photosynthesis, stomatal conductance, transpiration rate	Ahmed *et al*. 2023
4	Drought	*Oryza sativa* L. (Rice)	0, 5, 10, 15, 25, 50 ppm	25 ppm ZnO NP alleviates drought-induced damages	Mazhar *et al*. 2022
5	Drought	*Solanum tuberosum* L. (Potato)	2.50 and 5 ppm	Improves drought stress	Sallam *et al*. (2022)
6	Water Stress	*Triticum aestivum*	10mg/L	Enhances growth, grain yield, crop water	El-Bassioumg

		(Wheat)		productivity	*et al*. (2022) [10]
7	Arsenic (As) toxicity	*Oryza sativa* L. (Rice)	0, 10, 20, 50, 100 mg/L	Enhances growth and photosynthesis, decreases arsenic accumulation in shoots	Yan *et al*. (2021) [46]
8	Arsenic (As) toxicity	*Glycine max* (Soybean)	0, 25, 50, 100 mg/L	Alleviates arsenic toxicity in soybean plant	Ahmad *et al*. (2020)
9	Cadmium	*Lycopersicon esculentum* (Tomato)	50 mg/L	Reduces adverse effects generated by cadmium	Faizan *et al*. (2021)
10	Cadmium	*Zea mays* L. (Maize)	0, 50, 75, 100 mg/L	ZnO NP alone or in combination with biochar reduces electrolyte leakage, malondialdehyde, hydrogen peroxide content	Rizwan *et al*. (2019) [22]
11	Cadmium	*Oryza sativa* L. (Rice)	50 mg/L	Improves photosynthesis, biomass, protein, mineral nutrient content antioxidant enzyme activity,	Faizan *et al*. (2021)
12	Cadmium	*Triticum aestivum* (Wheat)	0, 25, 50, 75, 100 mg/kg	Enhances cadmium stress tolerance	Hussain *et al*. (2018)
13	Chilling	*Oryza sativa* L. (Rice)	25, 50, 100 mg/L	Alleviates chilling stress via the mediation of antioxidant system and chilling response transcription factors	Song *et al*. (2021) [42]
14	Cobalt stress	*Zea mays* L. (Maize)	500 mg/L	Ameliorates cobalt stress	Salam *et al*. (2022) [40]
15	Heavy metal	*Leucaena leucocephala*	(0, 25, 50, 75, 100, 150, 200) mg/L Pb (NO$_3$)$_2$ concentration; (0,10, 20, 30, 40, 50, 75, 100) mg/L CdCl$_2$ concentration	ZnO nanoparticles at suitable concentrations reduce toxic effects of Cd and Pb	Venkatachalam *et al*. (2017)
16	Salinity	*Trigonella foenum-graecum*	0, 1000, 3000 ppm	Reduces salinity stress	Noohpisheh *et al*. (2021) [34]
17	Salinity	*Triticum aestivum* (Wheat), *Oryza sativa* L. (Rice)	–	Improves plants conditions	Mazhar et el. (2023) [31]
18	Salinity	*Oryza sativa* L. (Rice)	50 mg/L	Protects root tissue morphology, enhances nutrient and water transport	Singh *et al*. (2023)
19	Salinity	*Brassica napus* (Rapeseed)	–	Enhances plant growth and development	El-Badri *et al*. (2021) [9]
20	Salinity	*Solanum lycopersicum* Mill. (Tomato)	15 and 30 mg/L	More effective at 15 mg/L concentration than 30 mg/L concentration	Alharby *et al*. (2017)

Harmful impacts of ZnO nanoparticles in plants

ZnO NPs includes potential beneficial effects in mitigating abiotic stress and regulating plant growth. But in addition to its large significance it also possess some potential harmful impacts associated with their use in plants. ZnO NPs at higher concentrations show greater reactivity, leading to ROS production (Manke *et al*., 2013) [29], and have been reported to induce phytotoxicity, resulting decrease in plant growth, photosynthesis, and harvest. In relation to the hazardous consequences of NPs, various researches have been conducted on aquatic life because NPs discharged into the environment ultimately end up in water (Kahru and Dubourguier, 2010). This can occur due to aggregation of ZnO NPs in plant tissues, leading to oxidative effects and disruption of cellular functions. ZnO NPs have been proven to be significantly more hazardous when exposed to natural sunlight than those exposed to laboratory lights or dark conditions (Ma *et al*., 2011). While ZnO NPs can enhance the absorption of mineral nutrients in plants, their overuse can lead to altered nutrient uptake, causing nutrient imbalances and toxicity in plants. ZnO NPs can affect soil microbial communities, altering their composition and diversity, leading to potential fluctuations in soil fertility and nutrient cycling. It is vital to use ZnO NPs with caution, considering their potential harmful impacts and ensuring their safe use in agriculture (Peralta-Videa Jose *et al*., 2014) [36].

Conclusion

The unique properties of zinc oxide nanoparticles present an effective approach for sustainable agriculture by increasing plant growth and productivity. ZnO NPs have demonstrated positive outcomes in alleviating abiotic stress in plants, including improved photosynthesis, antioxidant activity, mineral nutrient uptake, and regulation of gene expression. However, it is essential to consider the potential hazards of ZnO nanoparticles based on their dimension, dosage, and the specific plant species involved. For secure and efficient utilization of ZnO nanoparticles, it is crucial to acquire a thorough comprehension of their optimal size, concentration, and interaction with plants. Moreover, the release of ZnO NPs from treated plants into the nature might cause risk to untargeted species such as soil microorganisms, hydrophytes, and human health. Further research is warranted to evaluate the long-term consequences and potential risks linked to the utilization of ZnO nanoparticles in agricultural applications.

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