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Role of Zinc Oxide Nanoparticles in Mitigation of Drought and Salinity

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A B S T R A C T

Currently agriculture is facing challenges like increase in global population, hunger and extreme poverty due to which rate of agricultural yield increase has declined. The main reason behind declined agricultural yield is abiotic stresses suffered by sessile plants. Salinity and drought are two major abiotic stresses which result in yield losses for example it is estimated that drought and salinity may cause 50% loss in crop production. In the fast moving world, a new technique of nanotechnology is adopted to overcome this problem. Zinc oxide nanoparticles are the particles which have dimension between 0-100nm. Zinc is one of the most important micronutrient used in different physiological processes like hormone biosynthesis, synthesis of chlorophyll and cofactor of enzyme like carbonic anhydrous, superoxide dismutase etc. Zinc oxide nanoparticles on the other hand are are less toxic, comparatively inexpensive and biocompatible nanoparticles as compared to other metal oxide nanoparticles because zinc does not interact with the majority of pharmaceutically active molecules. ZnO has been "generally recognized as safe (GRAS)" material by the Food and Drug Administration and is utilized as a food additive. Zinc oxide nanoparticles have potential for mitigating abiotic stress like salinity and drought as they are involved in synthesis of auxin which in turn activate cell division and enlargement, maintain integrality of biomembranes, accumulation of phospholipids, improvement in protein synthesis, scavenging free oxygen radicals, nutrient translocation from the aged cells to newborn cells, decreasing the uptake of excess of Na^+ and Cl^- and Zn also play an important role in opening and closing the stomatal pore and controlling the process of photosynthesis and alters the stomatal conductance and transpiration. In this review, use of zinc oxide nanoparticles to mitigate the effects of abiotic stresses in order to increase the yield potential of crops are discussed

Introduction

Zinc an essential nutrient

The process of diffusion enables the Zinc micronutrient to reach the plant roots but dry soil and less organic matter impair this process (Marschner, 1993; Rengel, 2015). As a consequence Zinc absorption through roots decreases which leads to less accumulation of Zinc in plants. This also results in reduced yield depending upon Zinc deficiency severity. In these conditions, application of Zinc fertilizer to soil/plant is a reliable approach ensuring appropriate uptake of Zinc in optimum concentration by roots (Cakmak *et al.*, 1996; Rengel, 2015). Elevated pH level enables the Zinc to bind tightly to soil particle and cell wall which reduces Zinc acquisition and uptake by roots from rhizosphere. Moreover, additional factors like total sulphur content, bicarbonates and soil redox potential affects the Zinc uptake in anaerobic condition (Impa *et al.,* 2012). Zinc deficiency causes severe impacts on human heath, especially in children, like impaired physical growth, weakened immune system and learning ability, and causing DNA damage and cancer development (Keenamp and Gershwin, 1990). The major role of Zinc in biological systems is, maintaining structural and functional integrity of biological membranes, protein synthesis and gene expression. Nearly half of the soils where cereals are grown have levels of available Zinc low enough to cause Zinc deficiency (Alloway, 2009).

Importance of zinc in plants

Zinc is one of the most essential nutrients required by all living organisms. It is the 23rd most abundant element (Broadley *et al.*, 2007) and the 2nd most abundant transition metal (Jain *et al.*, 2010). In plants zinc play an important role as it constituent or cofactor of many enzymes belonging to various classes like oxidoreductases, transferases, hydrolases, ligases, and isomerases (Auld 2001). These enzymes play important role in many biochemical pathways mainly concerened with metabolism of carbohydrates it include both photosynthesis and conversion to sucrose and starch also it work as cofactor of carbonic anhydrase which increases the carbon dioxide concentration of chloroplast, and thus also increases the carboxylation capability of the Rubisco enzyme (Salama *et al.*, 2006) lipid metabolism, protein metabolism and nitrogen. Zinc is involved in the biosynthesis of plant hormones like like auxin Abscisic acid, Gibberellin and Cytokinin, cytochrome, formation of pollen and maintaining integrality of cell membrane, synthesis of chlorophyll through the protection of the sulfydryl group, chloroplast development, some of their functions, such as the repair process of the photosystem II by 'recyclation 'of the D1 protein damaged by the light radiation or activity of the SPP peptidase and cell division (Sarwar *et al.*, 2013; Sturikova *et al.*, 2018). It also plays a very important role in regulating ion balance in plant (Vazin 2012). Also, one of the other effects of Zn is in increasing in the levels of antioxidants in plant tissues as it works as cofactor of enzymes like such as superoxide dismutase, catalase. Zinc plays a fundamental role in protecting and maintaining structural stability of cell membranes (Cakmak, 2008, Cakmak, 2010). Zinc ions are also part of the transcription factor family, known as 'zinc fingers' that control the proliferation and differentiation of cells. It also regulates the functions of stomata by retaining potassium content of protective cells.

Zinc in salinity mitigation

Zinc plays an important in mitigating the adverse effect of salinity in plants. It is hypothesized that zinc mitigates salinity by (1) synthesis of auxin which in turn activate cell division and enlargement (2) maintain integrality of biomembranes (3) accumilation of phospholipids, (4) improvement in protein synthesis (5) scavenging free oxygen radicals (6) nutrient translocation from the aged cells to newborn cells (7) Decreasing the uptake of excess of Na^+ and Cl^- (8) K and Zn play an important role in opening and closing the stomatal pore and controlling the process of photosynthesis. Therefore, high concentrations of K^+ in the stroma are required to maintain an optimum photosynthetic capacity under salinity stress conditions. Thus, maintaining the Na^+/K^+ ratio is the most important factor in salinity tolerance. Foliar application of zinc in wheat and mustard mitigate the harmful effects of salinity by restriction of sodium and chloride ions and absorption and compartmentation of important nutrients (Torabian *et al.,* 2016; Fathi *et al.,* 2016).

Leaf application of zinc under salinity decreased negative effects (plant biomass, water connections, gas exchange characteristics, and plant production in rice ((Ashraf *et al.,* 2014). Vojodi Mehrabani *et al.,* (2017) found that spraying zinc on *Lavandula stoechas* in saline condition alleviated the negative effects. Treatment of zinc helped rice plant to recover from the salinity depression by preventing Na^+ ion uptake, maintaining membranes integrity, better chlorophyll synthesis. Foliar spray of zinc increased accumulation of zinc, enhance K accumulation in plant tissue, reduce osmotic potential and increase turgor pressure in lavender plants under saline condition.

Role of zinc in drought mitigation

Zinc can affect the plant water relations as it alters the stomatal conductance and transpiration. The concentration of zinc effects the activity of zinc dependent enzyme like carbonic anhydrase, which regulates the CO_2 sensing pathway and is related to drought tolerance (Tewari *et al.,* 2019) and SOD and catalase involve in antioxidant defense pathway under drought stress (Yavas and Unay, 2016). Karim *et al.,* (2012) found that zinc foliar application did not affect wheat grain yield under well watered condition, but increased grain yield and concentration of zinc in the grain under drought. Sultana *et al.,* (2016) found that foliar Zn application counteracted the adverse effect of water deficit on wheat yield.

Nanobiotechnology

Nanobiotechnology is the new technology which involves the designing, characterization and application of material in nano size (100nm or less). This technology is widely used in the field of medicine, public health, trade and industry but its application in field of agriculture is at naïve stage and its use is increasing in this field as evicted by number of publication and patent granted (Kah *et al.,* 2019). Nanoparticles increase growth and protect plants against a variety of abiotic stresses due to the small size, structural properties, and higher surface-tovolume ratio (Khan *et al.,* 2014). In contrast other properties make them harmful leading to oxidative stress and cytotoxicity, and genotoxic responses. The degree of effectiveness or toxicity depends upon the chemical structure, size, surface area, reactivity and concentration used.

Why zinc oxide nanoparticles?

Zinc oxide nanoparticles have very small size enhancing the absorption, translocation, accumulation and assimilation in more dynamic way than the more common form of metal. ZnO nanoparticles are less toxic, comparatively inexpensive and biocompatible compared with other metal oxide nanoparticles because zinc does not interact with the majority of pharmaceutically active molecules (Sahdev *et al.,* 2013). ZnO has been listed as a “generally recognized as safe (GRAS)” material by the Food and Drug Administration and is utilized as a food additive.

Involvement of zinc oxide nanoparticles growth and development

Shahhoseini *et al.,* (2020) conducted as study to investigate the effects of zinc oxide nanoparticles (ZnONPs) on yield, metabolites content, and zinc and iron absorption of Feverfew. Nanoparticles at all concentrations increased the biological yield, essential oil content, and Zn absorption. Sadak and Bakry (2020) studied the effect of different concentration on nano ZnO (20, 40, and 60 mg/l) on various morpho-physiological parameters. Foliar application of 60 mg/L was found to be most effective for parameters like 1000 seeds wt. oil percentage; and seed, oil, biological, and straw yield/fed whereas concentration of 40 mg/L was effective for photosynthetic pigment content, shoot and root length, and shoots and root fresh and dry weight also zinc oxide in nano form significantly increased free amino acids, proline, and total carbohydrates of flax plants.

Bala *et al.,* (2019) investigated the effect of different concentration of zinc oxide nanoparticles in *Oryza sativa* plants. Foliar application of 500 to 5000 ppm increased growth and yield indices (height and shoot and root fresh and dry weights). Foliar application of zinc sulfate and zinc nanoparticles that positively affected the fresh weight of *Coffea arabica* (Rossi *et al.*, 2019). Garcia-Lopez *et al.,* (2019) found that 1000 ppm concentration of zinc oxide nanoparticles cause increase in height, stem diameter, chlorophyll, fruit yield, and total biomass and 2000 ppm increase in the total fruit, capsaicin content, dihydrocapsaicin, total phenols, total flavonoids (soluble + bound), and antioxidant capacity in fruits in habanero pepper plant. Seydmohammadi *et al.,* (2019) used three concentrations of zinc oxide nanaoparticles (3, 6 and 9 mg/L) to test the effect on the growth and flowering of lisianthus. It was found that foliar application of nano ZnO (6 mg/L) increased number of leaf and lateral branches, leaf chlorophyll content and petal anthocyanin content and number of flowers.

Siddiqui (2018) found that application of ZnO NPs at 0.50 ml/L caused a greater increase in plant length, carotenoids, H_2O_2, chlorophyll, SOD, CAT, APX, PAL and proline contents and GSH contents followed by application of ZnO NPs with 0.25 ml/L^{-1}. Xu *et al.,* (2018) reported that the ZnO NPs, at 10 mg/kg, enhanced the photosynthesis and biomass lettuce.

The possible reason for enhanced photosynthesis is due to an improvement in carbonic anhydrase, which could have facilitated the supply of CO2 to the sites of carboxylation in the chloroplast. Singh *et al.,* (2018) reported that nano ZnO (at 50 ppm) was the best treatment for increasing rice seedling growth and improving physiological processes. López *et al.,* (2018) found zinc oxide nanoparticle improved seed germination rate during the first seven days, seed vigor germination whereas zinc oxide nanoparticles did not affect plumule development, but they had a significant impact (p 0.01) on radicle length.

Rameshradd *et al.,* (2017) investigated the impact of Zn Oxide (ZnO) nanoparticles on Zn uptake, translocation and growth performance in rice in comparison to conventional Zn fertilizer ($ZnSO_4$). Seed priming with nano zinc showed improved plant height, chlorophyll content, biomass, tiller number and yield. The Zn content in leaf and seed is also higher in ZnO nano treated plant samples compared to $ZnSO_4$ treatment. Mankad *et al.,* (2017) assessed the effect of zinc oxide nanopaticles and their bulk counterpart rice and found out that nanoparticles treatments at lower concentration enhanced shoot and root length, fresh and dry weight, total chlorophyll and protein content along with seedlings antioxidant enzyme status superoxide dismutase, catalase and peroxidase. Tiwari *et al.,* (2017) found in maize that zinc oxide nanopaticles at of 500 to 2000 ppm of seed treatment and foliar treatment resulted in higher seed vigor, forage yield, grain yield, and higher zinc content. Mohsenzadeh and Moosavian (2017) reported the foliar application of zinc-sulfate and nano-zinc oxide positively affected the antioxidant enzymes activity as well as phenolics, proline, and chlorophyll content of rosemary (*Rosmarinus officinalis* L.).

Rameshraddy *et al.,* (2017) showed that ZnO-NPs (1000ppm) improve seed vigor of 45.54% with treatments of while at 1500 ppm a significant reduction of this parameter was observed in seedling of *ragi* (*finger millet*). Venkatachalam *et al.*, (2017) used zinc oxide nanoparticle of size 2-54 nm at different concentration of 25, 50, 75, 100, and 200 mg/L and found that growth and photosynthetic pigment content increases with the increase in dose.

Upadhyaya *et al.,* (2016) reported an exposure to ZnO nanopartcles at different concentration caused significant changes in radicle and plumule length, fresh, dry weight and seed moisture content in rice also antioxidant enzymes increased due to ZnNP treatment suggesting that ZnO nanoparticles may significantly alters antioxidant metabolism during rice seed germination. Singh *et al.,* (2016) compared the effect of common $ZnSO_4$ with ZnO nanoparticles on germination, seedlings viability, chlorophyll content, proteins, carbohydrates, and eventually the intensity of antioxidant activity (SOD) and lipid peroxidation (malondialdehyde) in tomatoes. Positive effect nano zinc oxide was on observed parameters of the plant at a lower concentration (1.2 mM) in comparison with $ZnSO_4$. Higher concentrations of nanoparticles (6.1 mM). Amooaghaie *et al.,* (2016) found that zinc oxide nanoparticles in concentration(50 mg/ L)increased the root tolerance index (RTI) and seed germination tolerance index (GTI) in wheat. Adhikari *et al.,* (2016) found that maize seeds coated with ZnO nanoparticles show better germination percentage (93-100%) due to ZnO coating as compared to uncoated seeds (80%). Subbaiah *et al.,* (2016) reported ZnO NPs significantly influenced the growth, yield, and Zn content of maize grains. Zafar *et al.,* (2016) found that application of ZnO-NPs to seeds of *Brassica nigra*, obtaining a negative effect in the root growth and resulted in an increase of 79% of DPPH radical scavenging activity and an increase in phenolic compounds was also obtained.

Farnia and Omidi (2015) reported positive increase in grain row per cob, number of grain per cob and grain yield of maize due to application of nano Zn fertilizer. Vafa *et al.,* (2015) found growth parameters of savory plant; height, leaf number, leaves fresh and DW, chlorophyll, essential oil and phosphorus content were improved by nano-zinc application. Javadimoghadam *et al.,* (2015) found concentrations of nanoparticles increased fresh and dry weights; in other words, the biological yield, relative to the control, indicates the positive effects of nanoparticles. Gokak and Taranath (2015) reported the improvement of characteristics associated to physiological quality of the seed may be attributed to NPs inducement of photosensitization reactions and photo-generation of active oxygen such as superoxide and hydroxide anions. These reactions stimulate the ion penetration and promote water and oxygen imbibition, necessary for rapid germination.

Ramesh *et al.,* (2014) found that lower concentrations of ZnO NPs had beneficial effects on the seed germination of wheat. Mukherjee *et al.,* (2014) while working on green peas exposed to different forms of zinc particles which includes bulk, nano and coated zinc particles found more tolerance in green pea plants treated with nano zinc.

Rezaei and Abbasi (2014) reported that application of nano-chelate zinc improves physiological processes in cotton plant; increases chlorophyll content and antioxidant enzyme activity. Jayarambabu *et al.,* (2014) studied the effect of ZnO nanoparticles on mungbean seeds (*Vigna radiata* L.) and revealed a significant improvement in germination, root length and shoot length at lower concentration. Laware and Raskar (2014) tested foliar application of zinc oxide nanopartcle growth parameters like plant height and number of leaves per plant were determined at the time of flowering and the seed yield contributing parameters like number of seeded fruits per umbel, seed yield per umbel and 1000 seed weight was determined at the time of harvest. Seed samples obtained from NP treated plants along with control were tested for germination and early seedling growth. The plants treated with ZnO NPs at the concentration of 20 and 30μg ml^{-1} showed better growth and flowered 12-14 days earlier than the control. Treated plants showed significantly higher values for seeded fruit per umbel, seed weight per umbel and 1000 seed weight over control plants. Helaly *et al.,* (2014) documented that adding nano-ZnO to MS medium enhances the activity of antioxidant enzymes in banana (*Mousa sapientum*), hence improving the abiotic stress tolerance.

Burman *et al.,* (2013) also found maximum response with respect to shoot dry weight and overall biomass accumulation in chickpea treated with 1.5 ppm of ZnO nanoparticles. Pokhrel and Dubey (2013) evaluated maize and cabbage seedlings against silver and zinc nanoparticles and reported similar increase in fresh weight at lower concentration. The enhancement in morphophysiological parameters may be attributed to accumulation of PGRs like cytokininins and gibberlins which plays an important role in cell division and elongation, respectively. De la Rosa *et al.,* (2013) investigated the effect of 50-1600 mg/ L ZnO NPs on cucumber, alfalfa, and tomato where it was extrapolated that seed germination was increased only in cucumber and the seed germination of tomato was reduced by merely 20% once were subjected to a concentration of 1600 mg/L ZnO NPs. Raliya and Tarafdar (2013) reported that ZnO NPs significantly improved plant biomass, shoot and root growth, root area, chlorophyll content, and protein synthesis in cluster beans. El-Kereti and El-Feky, in turn, applied nanoparticles of ZnO (13 nm diameter) to the peanuts in the form of a spray, The treatment had a positive effect on several characteristics at once (total content of the chlorophyll, content of essential fatty acids, zinc content, plant height and fresh weight), which indicates the suitability of this treatment for improving the agricultural properties of peanuts.

Prasad *et al.,* (2012) experiment was conducted that peanut seeds were separately treated with different concentrations of nano scale zinc oxide (ZnO) and chelated bulk zinc sulfate ($ZnSO_4$) suspensions (a common zinc supplement), respectively and the effect this treatment had on seed germination, seedling vigor, plant growth, flowering, chlorophyll content, pod yield and root growth were studied Treatment of nano scale ZnO (25 nm mean particle size) at1000ppmconcentration promoted both seed germination seedling vigor and in turn showed early establishment in soil manifested by early flowering and higher leaf chlorophyll content. These particles proved effective in increasing stem and root growth. Pod yield per plant was 34% higher compared to chelated bulk $ZnSO_4$.

Mahajan *et al.,* (2011) found that ZnO NPs promoted the root, shoot length, root and shoot biomass of *Vigna radiata* and *Cicer arietinum.* Boonyanitipong *et al.,* (2011) indicated that application of ZnO nanoparticles at concentration 10 mg/ L led to 100 % germination of rice seeds and little increase in root length and number of roots.

Pandey *et al.,* (2010) observed a positive response with ZnO NPs on seed germination and root growth of *Cicer arietinum*. ZnO nanoparticles affect the reactivity of phytohormones, especially indole acetic acid (IAA) which involved in the phytostimulatory actions.

Zinc oxide nanoparticles in salinity mitigation

Noohpisheh *et al.,* (2020) studied the effects of zinc oxide (ZnO) nanoparticles under salinity stress in two cultivars of *Trigonella foenum-graecum* and reported that the effects are cultivar and salinity dependent. Nanoparticle increased the concentration of calcium of root in one cultivar where it decreased in other. In addition zinc oxide nanopartice increased proline content and trigonelline content under salinity and normal condition.

Wang *et al.,* (2019) used zinc oxide nanoparticles (50 mg L^{-1}) for wheat seed priming and after 20 days recovery of priming the plants were exposed to salt stress of (200 mM NaCl) for 10 days. Priming of zinc oxide nanoparticles reduced the concentration of sodium and increased water.

The nanoparticles were effective in scavenging reactive oxygen species as exemplified by enhanced activity of various activities of antioxidant enzymes like SOD, APX and CAT leading to better homeostasis of ROS production. Priming also increased activities of phosphoglucomutase and cytoplasmic invertase which promoted the sucrose biosynthesis higher shoot dry weight, leaf proline concentration.

In addition photosynthetic rate was decreased by the nano-ZnO priming in wheat plants under normal condition. However, when exposed to salt stress, the nano-ZnO primed plants had significantly higher photosynthetic rate than the non-primed plants. Also, higher stomatal conductance and transpiration rate were found in nano-ZnO primed plants, compared with the non-primed plants. Hassanpouraghdam *et al.,* (2019) evaluated the role of nano zinc foliar application with two concentrations (0 and 3 mg L^{-1}) for salinity mitigation of NaCl salinity (0, 75, 150, and 225 mM) in plant *Rosmarinus officinalis*.

Foliar application showed positive effects on plant fresh weight, total flavonoids and zinc content under control condition without salinity. Nano zinc doubled the content of chlorophyll a and as a consequence total chlorophyll in non-saline (0 mM of NaCl) and saline-treated (≤ 150mMof NaCl) plants. Whereas these nanopaticles showed negative effect on concentration of chlorophyll b. Foliar application also decreased H2O2 (up to 22%) and MDA (up to 26.9%) content in plants grown at ≥ 150 mM NaCl and at 225 mM NaCl.

Vojodi Mehrabani *et al.,* (2018) used nano zinc and common form source of zinc under salt stress to study their effects on morphological and physiological traits of *Rosmarinus officinalis*. These nanopartcles showed show effect on elemental content (K^+, Na^+ and Zn^{2+}), as well as essential oil yield of the plants, also soluble sugars content, flavonoids, H_2O_2 and MDA contents were influenced by individual levels of salinity and zinc foliar applications. It was concluded that nano-zinc foliar spray was able to overcome the mild salinity effects on the plant growth and physiological parameters. Hussein and Baker (2018) found that the foliar application of nano-Zinc (200 ppm) led to mitigating the adverse effect of salinity and confirmed that diluted seawater could be used in the irrigation of cotton plant.

Latef *et al.,* (2017) to evaluate the effect of ZnO nanoparticles (20, 40 and 60 mg/l) on lupine plants (*Lupinus termis*) subjected salinity (150 mM NaCl). Treatment with ZnO nanoparticles (especially in 60 mg/l concentration) in plants stressed by salinity stimulated growth, promoted the formation of photosynthetic pigments, phenolic compounds, ascorbic acid and increased the activity of superoxide dismutase, catalase and other antioxidant enzymes.

Vojodi Mehrabani *et al.,* (2017) reported that Zn spraying in saline-treated Lavandula stoechas alleviated the negative effects (decreased dry weight) of salinity. Babaei *et al.*(2017) reported positive effects of zinc oxide naopaticles on biomass production and yield of wheat under salinity stress. Tawfik *et al.,* (2017) stated that nano Zn increased growth parameters of *Atriplex halimus*.

Torabian *et al.,* (2016) studied the effects of normal and nanoparticles of zinc oxide (ZnO) foliar application on the growth, proline content, and some antioxidant enzyme activities of sunflower cultivars at different salinity levels and reported higher shoot dry weight of sunflower in ZnO nanoparticles treatment compared to normal form which could be due to reason that mobility of the nanoparticles is very high, which leads to rapid transport of the nutrient to all parts of the plant. Due to its small size, the availability of the nanoparticle of ZnO can be higher compared to the normal form.

Alharby *et al.,* (2016) reported that ZnO NPs alter mRNA expression of SOD and GPX genes, and proteins in tomato (*Lycopersicon esculentum* Mill.) plant subjected to NaCl stress.

Taheri *et al.,* (2015) the nano-ZnO primed wheat plants had higher Fv/Fm than the non-primed plants under salt stress. This illuminated that the quantum yield of the PSII of wheat leaves under salt stress is enhanced by the nano-ZnO priming. The under salt stress. The ZnO NPs increase shoot dry matter and leaf area indexes. The effect of application of Hoagland solution containing ZnO and Fe2O3 nanoparticles in Moringa peregrine under salinity stress. The application of nanoparticles lower Na and Cl and higher N, K, Ca, Mn, Zn, and Fe. Lower Na storage is considered as an important indicator for salinity tolerance (Soliman *et al.,* 2015).

Zinc oxide nanoparticles in drought mitigation

Dhalim and Ajeel (2020) evaluate the effect of foliar application of different zinc source including zinc sulphate, zinc oxide and nano zinc at concentration of 100ppm in sunflower (*Helianthus annuus* l.) under different irrigation time and found highest level of auxine (IAA), Gibberline (GA3) in plants treated with the Nano-zinc treatment at concentration of 100ppm and treatment of 3 days interval irrigation. Plants irrigated every 9 days and treated with nano zinc oxide had the highest ABA compared to other treatment combinations. Nano-zinc application increased leaf content of zinc more than application of normal zinc. The highest values for leaf content of zinc (15.64 and 13.32 mg/g^{-1}) were recorded in the 3 days intervals. Upadhyaya *et al.,* (2020) studied the effect of zinc oxide nanoparticles for drought mitigation in rice. He reported that under drought stress there was decrease in root and shoot length the changes were comparatively lesser in ZnO treated plant and its interaction with 5 and 10% PEG treatment. Dry mass of shoot decreased due to water stress but it increased under ZnO NP and water stress in presence of ZnO NP treatment. The nanoparticle treatement did not show any significant difference in relative water content. Zinc content in both roots and shoot plant subjected to ZnO NP and its interaction with water stress increased. The activity of antioxidant enzymes CAT and POX increased mainly in shoot due to ZnO NP in both control and stressed plants but water stress resulted decreased in CAT activities. Sun *et al.,* (2020) investigated the effect of nano zinc at the concentration of (100 mg L^{-1}) in maize under drought stressed and well-watered maize.

The effect was studied on stomatal morphology, gas exchange and key carbon metabolism enzyme activities. It was found that the application of nanoparticle alleviated photosynthetic pigment degradation and benefited the stomatal movement, maintained a higher net photosynthetic rate, and enhanced water use efficiency, promoting the drought tolerance in maize also it increased the activity of UDP-glucose pyrophosphorylase, phosphoglucoisomerase and cytoplasmic invertase by 17.8%, 391.5% and 126% respectively, which enhanced the starch and sucrose biosynthesis and glycolysis metabolism in leaves under drought stress and concluded that these nanoparticles have potential to alleviate ill effect of salinity.

Dimkpa *et al.,* (2019) evaluated harmful effects of drought in sorghum and whether ZnO nanoparticles (ZnO-NPs) might alleviate such effects. It was found that under drought flag leaf emergence and heading were were delayed 6-17 days but application of zinc oxide nanoparticles reduced the delay by 4-5 days. Drought significantly ($p < 0.05$) reduced (76%) grain yield; however, ZnO-NP amendment under drought improved grain (22-183%) yield. Drought lowered (32%) average grain Zn concentration; however, ZnO-NP amendments improved (94%) grain Zn under drought.

Taran *et al.,* (2017) showed that Zn-nanoparticles decreased the negative effect of drought action on wheat seedling by increasing the activity of antioxidative enzymes reduced the level of accumulation of thiobarbituric acid reactive substances (TBARS) and stabilized the content of photosynthetic pigments and increased relative water content in leaves. Pavithra *et al.,* (2017) reported plants treated with ZnO NPs (1000mg/L) show improved plant height, chlorophyll content, biomass, tiller number, and yield. It improves drought tolerance of rice plant by maintaining the membrane stability and higher expression of Cu/Zn SOD. Yang *et al.,* (2017) reported zinc oxide nanoparticles induce remodeling of root morphology by increasing lateral root formation in wheat under drought stress. Sedghi *et al.*, 2013 studied the effects of different concentration of zinc oxide nanoparticles (0, 0.5, 1 g/ lit^{-1}) on drought stress imposed by poly ethyl glycol and found that zinc oxide nanoparticles at low concentration increase germination rate and germination percentage, root length, root fresh and dry weight, seed residual fresh and dry weight.

In conclusion, modern age nanotechnology is fast growing technology and nanoparticles are used intensively and becoming a part of the human life. However, the applications on nanotechnology and use of nanoparticles in sustainable agriculture and crop improvement are still at juvenile phase. Therefore, in order to harness the peculiar and unique properties of NPs in agriculture sector to get maximum potential advantages, it has become necessary to build up basic understanding regarding interaction of NPs with plants at cellular as well as molecular level. Zinc oxide nanoparticles have very small size enhancing the absorption, translocation, accumulation and assimilation in more dynamic way than the more common form of metal. ZnO nanoparticles are less toxic, comparatively inexpensive and biocompatible compared with other metal oxide nanoparticles. ZnO has been listed as a “generally recognized as safe (GRAS)” material by the Food and Drug Administration and is utilized as a food additive thus zinc oxide nanoparticles can be used for mitigation of different abiotic stress.

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