J. Appl. Biosci., 51(1): 47-54, June, 2025
doi: 10.61081/joab/51v1i103

ISSN (Print) 0975-685X
ISSN (Online) 0975-864X

REVIEW ARTICLE

Role of Zinc in Mitigating Drought Stress and Enhancing Resilience in Maize (*Zea mays* L.)

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ABSTRACT

This review examines the impact of drought stress on maize and the role of zinc (Zn) in enhancing drought resistance. Maize is a vital crop in India, but its productivity is severely impacted by abiotic stresses, drought in particular, which impairs its growth, physiological processes, yield, and nutritional quality. Drought stress leads to reduced plant height, leaf area, and photosynthesis, ultimately impacting kernel production. Zinc is an essential micronutrient involved in chlorophyll synthesis and stress regulation. This review highlights the mechanisms by which Zn enhances maize's resilience to drought, including improved root development, increased water absorption, and enhanced expression of aquaporins (AQPs). Furthermore, it discusses agronomic strategies for Zn biofortification, such as foliar application and seed priming, to mitigate Zn deficiency in maize grown in zinc-deficient soils. The genetic basis of Zn accumulation in maize is also explored, emphasizing the potential of quantitative trait locus (QTL) mapping and marker-assisted selection to develop zinc-enriched, high-yielding varieties. This review aims to highlight how zinc can improve drought tolerance and nutrition in maize, thereby enhancing food security in the face of climate change.

KEY WORDS: Aquaporins, Drought resistance, Essential micronutrient, Quantitative trait locus mapping, Zinc biofortification

INTRODUCTION

Maize (*Zea mays* L.*)* belonging to family Poaceae a major cereal crop in India. It is seasonaly cultivated in states like Karnataka, Madhya Pradesh, Bihar, Tamil Nadu, Telangana, Maharashtra, and Uttar Pradesh. According to the Second Advance Estimates released on March 10, 2025, the Ministry of Agriculture and Farmers Welfare projected India's maize production at 35.67 million metric tonnes for 2023-24, with an increase to 37.249 million metric tonnes in the 2024-25 season. This makes India the 5th largest producer (Source: FAO, updated as of 01-12-2023) and the 14th largest exporter of maize in the world (Source: UN-COMTRADE data 2022). Additionally, in 2023–2024, the nation exported 1,442,671.48 metric tons of maize worldwide, with a total value of Rs. 3,660.10 crores (USD 443.53 million-APEDA 2023–24).

The maize production faces challenges by abiotic stresses which may significantly impact agricultural productivity and food security. Extreme heat, drought, heavy metal contamination, nutrient deficiencies, and mineral toxicity are examples of abiotic stresses (Pandey *et al.,* 2010). Droughts are hydroclimatic severe occurrences that cause extended periods of water scarcity, which have an effect on global food security and agricultural productivity in Indian summer monsoon (Singh *et. al.,* 2019). El Nino/ Southern Oscillation (ENSO) and Indian Ocean warming are intimately related to droughts in India (Singh *et al.,* 2019; Jastor.org, 2024). In plants, the synthesis and function of auxins, enzymes, lipids, and proteins all require Zn (Hossain *et. al.,* 2008). Many studies indicate that Zn has the potential to regulate maize's resistance to drought, the systematic knowledge regarding the mechanism, is lacking. This review examines the effects of drought on maize plants and zinc mineral content.

Impact of Drought Stress in Maize Plant

Drought stress negatively impacts the nutritional profile, plant growth, physiology, yield, and quality of

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maize. According to Menkir *et al.*(2008), deficit moisture stress in seedlings slows down growth, lengthens the vegetative growth phase, reroutes resources, and alters carbohydrate metabolism in the shoot and root systems. By upsetting the source-sink connection, a water deficiency during ear leaf emergence—along with the five or six leaves located near and above the ear leaf—also influences the rate of photosynthesis in the plant and ultimately affects kernel production (Agrawal *et al.,* 2012). Maize exhibits heightened vulnerability in its apical ear regions during the pre- and post-pollination stages due to impaired embryo development, reduced grain numbers, and increased sensitivity to water stress. (Chakraborti *et al.,* 2010). The details of these consequences and critical stages for drought in maize are given in table 1.

Table 1: Impacts of Drought stress on critical stages of plants

Stress	Critical Stages	Impacts
Drought	• Seedling • Plant height • Flowering • Grains	• Decreased plant height and leaf area • Leaf senescence • Increased ASI (anthesis silking interval) • Reduction of chlorophyll content and photosynthesis • Sensitive to diseases • Tassel and Ear abnormalities

Hormones involve in Drought Stress

Hormones control multiple plant functions like stress, plant growth, flower development, fruit ripening and metabolic process. The hormone abscisic acid (ABA) is responsible for responding to water stress (Zhang *et al.,* 2006). Hormones translocation that occurs in both the xylem and phloem allows for bidirectional transport means from down to upward and upward to downward. However, the increased pH of apoplast results in a high retention of ABA. The LEA proteins generated by ABA plays a significant role in maize's drought resistance potential. Additionally, gibberellins and endogenous cytokinin levels drop precipitously during the drought condition. The cytokinins slow down the aging process in foliage.

Physiology of Zn Related to Drought Stress

Relative water content (RWC) decreases in plant due to unavailability of water which can further create water stress (Farooq *et al.,* 2009). The decrease in leaf water potential brought on by the decreased RWC induces the stomata to shut which may reduce the rate of transpiration (Arbona *et al.,* 2013). Stressful conditions in plants lead to reduction in protein and enzyme levels, decrease in membrane permeability, and elevation of leaf temperatures. These changes primarily result in the disturbance of respiration, protein and amino acid synthesis, mineral nutrition, and photosynthesis (Sapeta *et al.,* 2013; Tiwari & Yadav.,2020).

Zinc as Critical Micronutrients

Zinc is critical micronutrient that means it is needed in small quantities in plants (Dubey & Pathak, 2024). Zinc is crucial for normal development of plants and animals (Pathak, 2021) and is essential for structure and regulatory function in plants (Tiwari & Yadav, 2020). Zinc plays an important role in improving chlorophyll content, photosynthesis, metabolism of carbohydrates, and synthesis of starch (Malviya, *et al.,* 2023). It also plays significant role in the metabolism of protein synthesis, auxin, pollen function, cellular membrane integrity and processes linked to immunity against certain infections (Ma *et al.,* 2017). Its shortage is often anticipated in soils that are rich in silicon and phosphorus, calcareous, sandy, or peat (Ma *et al.,* 2017). The materialization of insoluble Zn combinations results in significant degradation of accessible zinc. The insoluble zinc complexes that are created momentarily may contain hydroxides of magnesium. A zinc deficiency may result in elevation of reactive oxygen species and/or reduced activity of antioxidant. According to research using black gram (*Vigna mungo*), Cu/ZnSOD and CA activities may be utilized as markers of zinc shortage as they have a positive correlation with zinc availability (Pandey *et al.,* 2002a &b).

Zinc Uptake

There is a significant variation in zinc requirements and concentrations across plant species, which leads to changes in zinc absorption and translocation (Gupta *et al.,* 2016). Plant roots primarily take up zinc in its divalent form (Zn^{2+}); however, they can also absorb it as ligand-zinc complexes. There are two distinct mechanisms that plants utilize to absorb zinc in its divalent form, and these mechanisms are influenced by the ligands released by the roots (Gupta *et al*., 2016). A preliminary technique involves the efflux of reductants, which increases the solubility of zinc complexes and promote the release of zinc ions for absorption. These reductants are molecules with a low molecular weight and the ability to form stable complexes with zinc. The second process in this mechanism facilitates the inflow of zinc into root epidermal cells. According to Gupta *et al.* (2016), this method is observed only in the roots of grain crops. Additionally, water molecules are necessary for the passive absorption of zinc, which also leads to changes in zinc concentration within the root cells. A large number of genes either encode proteins are associated with zinc transport or influence the expression of genes necessary for zinc transport. The decreased

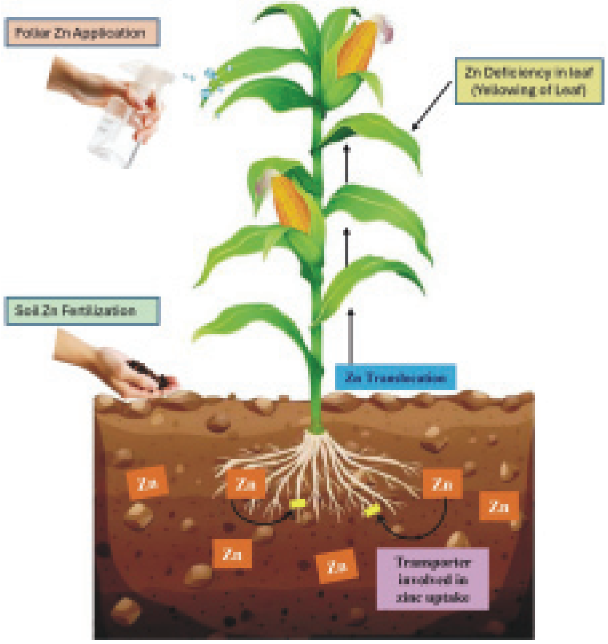

Fig. 1: Diagram showing Zn micronutrient uptake through soil and by foliar application in *Zea mays*

cytoplasmic activity that occurs due to metal sequestration and binding to intracellular sites, such as zinc finger proteins and enzymes, may affect the absorption of metal cations (Gupta *et al*., 2016). Zinc-deficient soils include alkaline soils, sandy soils, and phosphorus-rich soils (Klofác *et al*. 2023).

Considering the essential role of zinc in maize health, applying zinc foliarly can act as a nutritional boost, particularly in soils lacking sufficient zinc. Liu *et al.* (2016) demonstrated that foliar application of $ZnSO_4.7H_2O$ enhanced maize growth and Zn accumulation in tissues. Adequate Zn levels improved stomatal conductance, chlorophyll content, and photosynthetic efficiency, contributing to increased grain yields, though impacts on transpiration rates and boron uptake require further investigation. The efficacy of Zn fertilization depends on crop genotype and application method (Mao *et al.,* 2014). Foliar Zn application is particularly effective in ameliorating Zn deficiency in soils, supporting maize health and productivity. Zinc serves as a cofactor in enzymatic processes during critical growth stages, promoting development (Ma *et al.,* 2017) and enhancing water use efficiency through improved stomatal regulation and drought tolerance. In initial Zn fertilization trials, root development and shoot Zn content significantly increased, with reported increments varying by study conditions. In subsequent seasons, grain Zn content and harvest index improved by approximately 51% and 50%, respectively, relative to controls, though these outcomes are context-dependent.

Mitigation Strategies for Zn in Maize crop

Cereals have limited genetic potential to accumulate substantial amounts of zinc. Additionally, in low-income countries such as India and Iran, crops like maize are often grown in zinc-deficient soils (Alloway, 2009). The Green Revolution promoted the use of high-yielding crop varieties, advanced cultivation methods, and multinational fertilizers containing nitrogen, phosphorus, and potassium. However, irrigation and phosphorus application have an inverse relationship with zinc absorption, leading to reduced zinc levels in maize (Saha, 2014). Enhancing zinc levels in drought-stressed maize through biofortification may be achieved using various agronomic and breeding approaches. Zinc effect on antioxidative constituents suggested its involvement in sustaining the antioxidative defence system in maize leaves (Pandey *et al.,* 2002 b).

Techniques in Agronomy

Agronomic pre-sowing treatments include seed priming, soil preparation, and foliar zinc fertilizer. Zinc fertilization results vary by technique and grain type. Cereal mineral biofortification links agronomic methods and breeding strategies because varied mineral sources enable germplasm screening. Zinc content varies by soil type. Zinc is present in soils with a mean amount starting from five to 55 mg/kg. The normal zinc content in soil is 64 milligrams according to kilogram (Noulas *et al.,* 2018). Conversely, figuring out the edge stage is labelled as Zn poor is hard (as distinctive in Noulas *et al.,* 2018). The variations in overall Zn attention and the percentage of other hint elements are because of numerous environmental occasions. the threshold quantity for zinc deficiency inside the soil is determined the use of numerous exams. The consequences had been ascertained by means of the evaluation of the zinc attention within the soils. Zinc concentrations in sand, peat, and muck soils range from 10 to 30 mg/kg, a variety insufficient to save you zinc deficiency in plant life. This clarifies the connection between global zinc (Zn) deficiency in humans and the zinc shortage in soil. Zinc must be present in the soil to assess the absorption capacity according to genotype.

Maize seed priming

Seed priming process contains the treatment of seed with many kinds of solutions and nutrient medium and osmo-priming which involves soaking seeds in an osmotic solution to improve their quality and germination before planted the seed and hydro-priming that means soaking the seed in water. Maize grain yielding increases up to 27-30% when seed priming done by $ZnSO_4$ (Harris, 2007). Foliarzinc application and seed priming simultaneously enhances zinc concentration in maize (Mohsin *et al.,* 2014)

Zinc treatment on soil and leaves

Numerous studies have demonstrated the diverse impacts of foliar and soil zinc treatments on maize plants. Increasing Zn concentration influences zinc uptake and remobilization. However, the genetic processes controlling zinc retranslocation from leaves to grains under foliar treatments remain unknown. Applying zinc fertilizers to the soil was reported to increase zinc concentration in maize by 40% (Kanwal *et al.,* 2010). Zinc applied filially to maize and other grains raises iron content and lowers cadmium toxicity (Aref, 2010). Hossain *et al.* (2008) indicated that seed priming and adding zinc fertilizer to soil may increase the zinc content in maize. This not only enhances the nutritional profile of maize but also improves the dietary quality of communities that rely on it as a staple crop. Given the rising worldwide frequency of zinc deficiency, such agricultural treatments may be rather important in addressing public health issues concerning micronutrient malnutrition.

Foliar spray treatments result in limited zinc uptake by plants, with only 1%-5% of the applied zinc being absorbed (Zhao *et al.,* 2011). Zinc absorption is influenced by the type and rate of fertilizer used. Zinc sulphate ($ZnSO_4$), accounting for nearly 75% of zinc fertilizers, often becomes fixed in the soil, rendering it unavailable to plants. This fixation is more pronounced in alkaline soils ($pH > 7.0$) due to higher carbonate concentrations. However, gluconic acid can enhance zinc availability by solubilizing fixed zinc, making it accessible for root uptake. As a biodegradable compound, gluconic acid acts as a strong anion that facilitates zinc solubilization. Additionally, arbuscular mycorrhizal fungi (AMF) can improve zinc uptake from the soil (Suganya, 2015).

Vigorous mixing of zinc fertilizers into the soil boost zinc root uptake and improve zinc use efficiency. One key limitation is the spatial mismatch between maize root distribution and zinc availability in the soil profile. Consequently, effective subsurface Zn application is necessary to prevent root distribution mismatching and improve root absorption of Zn. Studies have shown that incorporating $ZnSO_4.7H_2O$ up to a 30 cm soil depth promotes favourable root development and zinc absorption. For effective uptake of zinc from the soil, the distribution of roots and the amount of zinc in the soil must coincide spatially (Zhang *et al.,* 2013).

Combined foliar and soil application of zinc fertilizers significantly increases zinc content in maize compared to individual applications. Interestingly, higher zinc levels are positively correlated with grain yield, 1,000 grain weight, and cob diameter and length (Mohsin *et al.,* 2014). Zinc fertilization have been observed to promote early vigorous growth, improved yields, and greater tolerance to abiotic stress (Welch *et al.,* 2004). Zinc fertilization is suggested to be beneficial in raising the Zn content; nevertheless, genetic variations in the genotypes of maize and the various agro-ecological zones in which the crop is grown may account for variations in the outcomes. Before utilizing various breeding techniques to enhance the features, it is important to comprehend the genetic basis of zinc concentration. Therefore, genetic underpinnings of the characteristic are explored here before moving on to techniques for gene enhancement of Zn content.

The genetic basis of zinc content in maize

QTL mapping has identified numerous genetic loci responsible for the genetic control for zinc build-up (Baxter *et al.,* 2013). Various mating designs, including the diallel mating design, have been applied in genetic studies to facilitate gene activation. Genetic research further supports the predominance of additive gene action for zinc content in maize leaves and ears (Chen *et al.,* 2007). Presence of additive gene action suggests that the performance of inbred lines can reliably predict hybrid performance for these traits. The gene responsible for zinc accumulation in maize genotypes has shown some conflicting findings. Qin *et al.,* (2012) discovered that partial dominance and over dominance influenced zinc accumulation in their QTL mapping. Similarly, Chakraborti *et al.,* (2010) found that non-additive gene action was predominant for zinc addition. Thus, a combination of both additive and non-additive gene effects could be utilized to enhance the zinc content in maize by selecting the best lines as parents (Menkir, 2008).

In any breeding program, heritability is a highly helpful biometric statistic to evaluate the effective transmission of genetic features from one generation to the next. Simic *et al.* (???) identify the 0.60 value for heritability of the zinc content in maize plant. The heritability of Zn content was found to be 0.69 by Baxter *et al.* (2013) based on QTL mapping studies. The degree of heritability variability demonstrated the significant role that genes or QTLs play in influencing the concentration of zinc. Additionally, QTL mapping studies showed transgressive segregants (Qin *et al.,* 2012). The development of Zn-enriched maize lines may be possible via transgressive segregants.

In plants, zinc and iron concentrations have a positive correlation. The connection between the genes controlling Zn and Fe levels may be the cause of this association. Numerous genes are known to be Zinc transporter genes, and some of these genes encoded proteins can transport several metals at once (Qin *et al.,* 2012). These characteristics' QTLs are likewise co-localized on the same chromosomal areas, according to QTL studies (Qin *et al.,* 2012). Results of the correlation study showed that maize Zn and Fe concentrations might be raised simultaneously. On the other hand, several contradictory results (Agrawal *et al.,* 2012) indicate that there may be little to no link between Zn and Fe contents. Different experiments report associations with varying magnitudes. The genetic heritage of the breeding material may be the cause of variations in the correlation findings (Gupta *et al.,*2015). It is extremely feasible to create high-yielding maize cultivars with higher zinc contents due to the positive nature of correlations.

Maize genetic enhancement for zinc biofortification

To improve zinc biofortification via genetic variety, many sophisticated breeding methods may be used like marker-assisted selection, quantitative genetics, and mutant. These methods use linkage maps and molecular markers to identify QTLs critical for phenotypic enhancement. Collard & Mackill (2008) assert that marker-assisted breeding is notably beneficial for zinc biofortification. Furthermore, contemporary innovations like high-throughput single-nucleotide polymorphism (SNP) technology have enabled the genetic improvement of zinc amount in plants, as shown by Mc Mullen *et al.,* (2009). Moreover, transgenic research has considerable promise for realizing extensive genetic enhancements in agricultural crops. This discourse seeks to emphasize the significance and promise of zinc biofortification in maize.

Raising the Zinc content

Developing biofortified maize genotypes involves raising the Zn content to understanding of the physiological, pharmacological, genetic processes underlying zinc. The mineral homeostasis has also been the subject of several prior investigations (Jeong *et al.,* 2009). To determine the Zinc contents in maize, Qin *et al.*(2012) crossed two contrasting parents to create an F2:3 mapping population of maize. These mapping populations showed significant genetic variety and transgression segregation at high heritability kernel Zn concentration. In order to identify QTLs, genetic analysis was performed in both individual and combined habitats.

Genetic improvements for mineral concentrations might be produced concurrently, according to connections between genotype and phenotype. Finding QTLs for mineral accumulation is a valuable tool that may be used in marker-assisted breeding to create genotypes that are higher in zinc. Studying the QTLs controlling the variance in mineral accumulation in the endosperm is also necessary. Studies that focus on endosperm are crucial because, whereas most minerals found in germ and aleurone layers are lost during milling, around 75% of the minerals found in whole grains are maintained throughout milling and processing (Ozturk *et al.,* 2006). To increase the Zinc in maize, diversity analysis is very helpful, as are traditional hybridization or selections that follow. Genetic engineering might be used to take advantage of a number of molecular pathways, including increased intake and remobilization in roots to all plant parts.

Antioxidant enzyme activity and root morphological characteristics are regulated by zinc. Water stress modifies the structure of plant roots, restricts crop development and grain production, and lowers yield. It has been shown that maize seeds with high zinc content may mitigate these effects, which worsen in the absence of zinc (Faran *et al.,* 2019). According to Grewal & Williams (2000), these data showed that zinc improved plants resistance to water stress from the early stage. When plants experienced drought, the application of 6µM Zn^+ PEG treatments led to a substantial increase in root dry weight, surface area volume, and length when compared to the application of Zn^+ PEG treatment. When zinc levels are either excessive or inadequate, these occurrences become more severe (Faran *et al.,* 2019). In contrast to earlier research, found that in our trials, moderate zinc never boosted and instead decreased enzyme activity of maize roots. Another argument for moderate zinc intake is that it increases water absorption, making maize less susceptible to drought; thus, low antioxidant enzyme activity results from a decrease in reactive oxygen species.

Zinc modifies the anatomical structure of root

In Maize plant water absorption happens between 4 and 15 cm from the tip of the root (Zhang & Xu, 2009). According to Karuppanapandian *et al.* (2011), a zinc excess or deficit may harm cells in a variety of organelles (Noctor *et al.,* 2018). According to research, zinc may have a role in maintaining membrane integrity by reducing antioxidant enzyme activity. Overexposure to zinc causes damage in plant cell and other damage to the ultra structure of root cells (Zhou *et al.,* 2017). In the current research, moderate zinc has been shown to enhance stress resistance and promote root cell integrity. The cross-section at the root tip's water-absorbing region under simulated drought conditions showed a significantly wrinkly metaxylem and some structural alterations. The areas of the protoxylem, pericycle, and endodermis were noticeably decreased. Six micrograms of zinc (Zn) or six micrograms of Zn^+ PEG preserved the integrity of the root and leaf while promoting root development.

Zinc controls the expression and activity of the genes encoding for AQPs, which in turn affects DNA synthesis and mitotic activity at the root tip (Jain *et al.,* 2010). These processes have an influence on root development (Ariani *et al.,* 2019). According to Sutka *et al.,* (2016), AQPs contribute to the plant stress tolerance and induce water loss in a variety of crops. According to some research, plants may be more resilient to water stress if their AQP gene expression is altered (Sade *et al.,* 2009). According to our findings, modest Zn-induced increases in PIP expression help maize roots absorb more water while they are under water stress. Root morphology and the expression of root AQPs are closely associated (Zargar *et al.,* 2017). According to Peret *et al.* (2012), there is a connection in auxin relation growth and tissue hydraulics that explains how AQPs aid in the promotion of lateral root development. Moderate Zn enhanced the expression of AQPs which leads to enhanced roots to absorb water, which may have been the primary cause of root development. AQPs may also affect the vascular system's resistance to long-distance water transport by controlling the permeability of xylem parenchyma cells (Kaldenhoff *et al.,* 2008). According to Zargar *et al.* (2017), AQPs support plants' ability to fend off oxidative damage, counteract the detrimental effects of an osmotic imbalance, and impede processes brought on by dryness. In contrast, following 48 hours of PEG treatment, the PIP expression in maize roots was lower in this research as compared to the control. While PIPs aid in water absorption during water stress, Bogeat-Triboulot *et al.* (2007) found that as stress increased in duration and intensity, AQP transcript levels decreased. As a result, PIPs gene expression tended to rise initially before declining as PEG stress duration increased. During rehydration after drought, PIP1 or PIP2 antisense mutants had reduced root hydraulic properties and a delayed recovery than their wild-type counterparts (Martre *et al.,* 2002). In response to Drought stress, mild zinc elevated the transcription level of root hydraulic conductivity-promoting PIPs. By encouraging water conduction via the cell-to-cell pathway, AQP increases water absorption in the root and, as a result, increases water conductivity across the whole root (Knipfer *et al.,* 2010; Gitto *et. al.,* 2018).

Under times of water stress, zinc preserves the water balance and encourages the development of maize

According to research by North *et al.* (2005), AQPs contribute to the reduction of root hydraulic conductivity in agave plants under water stress. Moderate zinc levels enhanced root conductivity in maize, but water stress caused a notable and substantial decrease in it. This suggested that moderate zinc's promotion impact on root conductivity was connected to AQPs. According to Hachez *et al.* (2012), crops under water stress had decreased photosynthetic and transpiration rates; however, cultivars treated with 6μM Zn^+ PEG showed enhanced review make them pre-proof. According to these findings, during drought circumstances, modest Zn increased transpiration and photosynthetic rates. Drought-induced reductions in photosynthesis are likely due to the destruction of chloroplast structure by water stress (Sairam *et al.,* 2000; Earl, 2002). The structural integrity of leaves deteriorates with decreasing leaf water potential. Water stress compromises the ultrastructure of leaves, which may contribute to the decline in water potential. However, moderate zinc supplementation helps preserve chloroplast integrity, mitigates structural damage caused by drought in maize leaves, and enhances photosynthesis under water stress. Improved photosynthesis indirectly increases the transpiration rate while also expanding leaf area. By enhancing transpiration pull and promoting root water uptake, this mechanism helps maize maintain its water balance under drought conditions.

CONCLUSION

This review highlights that even a small amount of zinc can improve the water uptake in maize, enabling it to adapt to environmental changes. The review also discusses the mechanisms by which zinc enhances maize water absorption under drought conditions. Root development metrics were significantly reduced under low Zn treatment, potentially leading to oxidative damage due to water stress. However, moderate Zn treatment enhances root hydraulic conductivity by promoting root development and increasing AQP expression. As a result, photosynthetic product accumulation is greater, and the structure of cell organelles is preserved. The rate of leaf transpiration was influenced by increase in shoot surface area and leaf water potential. In maize, moderate zinc levels enhance transpiration and root water absorption, helping to maintain water balance and prevent damage from water stress. Zinc plays a crucial role in enhancing maize resilience under drought stress by improving physiological, biochemical, and molecular responses. It contributes to antioxidant defence mechanisms, osmotic balance, and root development, thereby enhancing water uptake and reducing oxidative damage. Additionally, zinc regulates key enzymes and proteins involved in stress tolerance, leading to improved growth, yield, and overall plant health under drought conditions. Optimizing zinc fertilization strategies can be a practical approach to mitigating drought-induced losses in maize, supporting sustainable agriculture and global food security. Future research should focus on developing zinc-efficient maize varieties and refining application methods to maximize benefits under varying climatic conditions.

ACKNOWLEDGEMENTS

The authors are thankful to Head Department of Botany, University of Lucknow for providing necessary facilities.

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