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Mitigation of Abiotic Stresses in Plants through Nutrient Management

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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

The food demand over the world is increasing due to the rapid increase in the population. Direct and indirect effects of climate change have severely affected the growth and development of crops. Of these, abiotic stress factors are reported to cause a reduction in crop productivity ranging from 51 percent to 82 percent. Abiotic stresses like drought, waterlogging stress, salt stress, soil acidity, metal toxicities and temperature variations have overwhelming impact on the growth and productivity of crops. Abiotic stress causes increase in reactive oxygen species (ROS) levels and affects various physiological processes, causing reduction in plant growth and yield. Nutrient management proves to be an effective strategy for alleviating various abiotic stress factors affecting agricultural crops. Nutrients such as nitrogen, potassium, calcium and magnesium increase the production of antioxidant enzymes such as superoxide dismutase, peroxidase, catalase and reduces ROS production. Micronutrients such as iron, boron and zinc as well as biofertilizers improve plant adaptation to various stresses through activation of antioxidant enzymes. Current review focuses on the impact of mineral nutrients, organic amendments and biofertilizers in alleviating abiotic stress in agricultural crops.

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1. INTRODUCTION

Globally, the food demand is increasing as the population grows rapidly. It is estimated that by 2030, global food production will need to increase by 70% over current crop productivity [1]. In parallel, the direct and indirect effects of climate change are resulting in multiple abiotic stresses, which are exerting a detrimental impact on crop growth and the overall sustainability of the environment. The production of crops is currently facing significant challenges due to various abiotic stresses such as drought, extreme temperatures, floods, salinity, acidity, mineral toxicity and nutrient deficiency [2]. The collective repercussions of these factors can further deteriorate the conditions and result in a decline in productivity ranging from 51 per cent to 82 per cent [2]. The decline in average yields for most major crops by over 50 percent can be primarily attributed to abiotic stress factors [3,3a]. The major factors contributing to yield loss due to abiotic stresses shared by high temperature (20%), low temperature (7%), drought (9%), and other forms of stresses (4%) [4].

To sustain agriculture, it is essential to focus on the development and promotion of strategies that effectively minimize the impact of abiotic stresses. The major techniques employed to sustain crop yield levels during stressful periods include the adoption of improved nutrient and agronomic management practices, as well as the development of novel genotypes with enhanced capacities [5]. Sufficient nourishment is imperative for the effective functioning of all physiological processes as well as for preserving the structural integrity of plants. Plant growth and metabolism heavily rely on several key nutrients. Nitrogen, for instance, is an integral part of nucleic acids, while magnesium contributes to the structure of chlorophyll. Additionally, phosphorus is essential for energy production and storage, and potassium is crucial for osmotic regulation and the activation of diverse enzymes [6].

Agriculture is confronted with a crucial challenge in effectively managing abiotic stress. The adverse effects of abiotic stresses extend beyond individual farmers and their families, impacting national economies and the stability of food security. The various abiotic factors mentioned above induce osmotic stress in plant cells. This stress significantly affects crucial plant functions including seed germination, growth, development, photosynthesis and reproduction, ultimately leading to severe consequences for plant growth and yield [7]. The focus of this review is to elaborate on how the utilization of diverse nutrients and soil fertilization practices from various sources can aid in mitigating the major abiotic stresses that plants confront.

2. ECONOMIC YIELD LOSS DUE TO DIFFERENT ABIOTIC STRESSES

Agriculture is confronted with a crucial challenge in effectively managing abiotic stress. The adverse effects of abiotic stresses extend beyond individual farmers and their families, impacting national economies and the stability of food security [7].

The growth and development of crop plants are primarily influenced by abiotic stresses, such as high temperature, radiation, heavy metal stress, drought, waterlogging, salinity and environmental pollution. The impact of drought stress on crop yield is significant, resulting in a reduction of 47-87 percent in maize and 30-60 percent in rice [8]. Similarly, reports shows that salinity cause 2-7.2 per cent [9] and 15.1–60.1 per cent [10] reduction in yield of tomato and pearl millet respectively. Due to heavy metal stress, 10 per cent yield reduction was observed in maize [11]. Under various ecological conditions, the cumulative impact of these factors may lead to a decline in productivity, ranging from 51 percent to 82 percent [1]. The data presented clearly illustrates the alarming effects of abiotic stress on crop productivity, emphasizing the critical importance of mitigating these stressors effectively.

3. ROLE OF NUTRIENTS IN ABIOTIC STRESS

In general, nutrients such as nitrogen, potassium, calcium and magnesium increase the concentration of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) and reduce reactive oxygen species (ROS) during stress. Potassium and calcium, being essential nutrients, aid in the improvement of stomatal regulation and osmotic adjustments by enhancing water uptake [6]. These nutrients play a crucial role in preserving a favourable tissue water potential during periods of temperature stress. Iron, boron and zinc are essential micronutrients that facilitate the activation of numerous physiological alterations in plants, triggering defense mechanisms and enhance metabolic processes, enabling plants to effectively cope with various adverse stresses. Proper nourishment of plants is a highly effective approach to mitigate the impact of salt stress on crop plants. The provision of mineral nutrients to plants also plays a crucial role in enhancing their ability to withstand different environmental stresses such as drought, salinity, disease and temperature fluctuations [12]. Furthermore, the implementation of diverse nutrient combinations has proven to be efficacious in alleviating a wide range of plant stresses [1].

4. DROUGHT STRESS

Among the various environmental stressors, water proves to be a pervasive constraint on crop production at a global level. Drought refers to a prolonged period in a region where there is a lack of rainfall that falls below the statistical mean [13]. The agricultural sector is adversely affected by drought when there is a lack of moisture in the soil or when the available moisture is insufficient to support the growth of crops. Approximately 28 percent of the Earth's land is deemed too arid to sustain plant life, as per estimates. In the tropical regions, it has been projected that drought leads to an average annual reduction of 17 percent in crop yields [14].

The productivity of crops is diminished by the drought, leading to stomatal closure and a decrease in respiration. Additionally, the drought hampers the uptake of nutrients and triggers an overproduction of reactive oxygen species. This, in turn, results in the deterioration of cell membranes and disrupts the distribution of assimilates among various organs [15]. Oxidative stress occurs as a result of the limited absorption of nutrients from the medium, which is caused by the combined effects of salinity and drought [14].

4.1 Nutrient Management to Mitigate drought Stress

The crop that receives an appropriate quantity of specific nutrients demonstrates an enhanced capacity to withstand drought conditions [16]. Babaeian et al. (2011) [17] reported that application of iron (Fe), and zinc (Zn) together with manganese (Mn) have increased proline concentration, carbohydrate biosynthesis resulting in a yield appraisal by 5.5 per cent in sunflower.

Similarly, application of nitrogen (N), phosphorus (P) and potassium (K) nutrients increased grain yield by 7 per cent and 122 per cent in wheat and sorghum respectively [18,6]. An increase in height of plants and relative water content (RWC) was observed after Fe supplementation [19]. Application of ZnO, B_2O_3 and CuO at a rate of 1.77, 0.80, and 0.92 g L^{-1} respectively, showed an increase in biomass production coupled with an increase in N, P and Zn uptake in soybean and cucumber under drought condition [20]. An increase in chlorophyll a and b content, relative water content, water potential, carotenoids, ascorbate peroxidase, seed yield and plant dry mass was observed through application of 4 g kg^{-1} Fe solution in fennel [21]. According to Aown et al*.* [22] application of K resulted in an increased plant height, spike length and yield (21%) in wheat crop [22a].

The application of silicon (Si) also aids in mitigating drought stress in crops by stimulating seed germination, enhancing root length, increasing root surface area, improving plant biomass, and boosting yield. The positive impacts are ascribed to the deposition of Si in the cell walls of roots, leaves, culms, and hulls. The silicon cellulose membrane present in the epidermal tissue of rice serves as a protective barrier, preventing the plant from losing an excessive amount of water through transpiration. This action takes place as a result of a decrease in the diameter of stomatal pores, which subsequently leads to a reduction in leaf transpiration [23]. Exposure to drought stress decreased rice growth significantly and exogenous application of 1.5mM silicon significantly increased plant dry matter and enhance drought resistance. In maize, application of Zn and K reduced the drought stress and resulted in high grain yield when K and Zn were applied at the rate of 150 kg ha^{-1} K and 12 kg ha^{-1} Zn respectively [24].

The application of biofertilizers enhances the production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which aids in the breakdown of plant ACC. This process effectively prevents the accumulation of ethylene and enables plants to withstand water stress [25]. Additionally, the exopolysaccharides generated by plants enhance the soil's capacity to retain water. The presence of plant growth promoting rhizobacteria (PGPR) stimulates the production of osmolytes, thereby effectively mitigating the harmful impact of reactive oxygen species (ROS). The presence of arbuscular mycorrhizal fungi (AMF) in rice plants promotes drought tolerance by improving stomatal conductance and chlorophyll fluorescence [26]. The application of biochar and AMF as amendments during inoculation had a positive impact on the nitrogen fixation attributes of the plants. Notably, it led to an increase in the number and weight of nodules, elevated levels of leghemoglobin content and enhanced activity of the nitrate reductase enzyme [27]. The upregulation of the antioxidant system and prevention of ROS accumulation and oxidative stress are facilitated by both biochar and AMF. This is achieved through an increase in phytohormone production, which in turn induces crosstalk between stress responsive gene products and the induction of systemic resistance.

4.2 Waterlogging

Waterlogging refers to the phenomenon of natural flooding and excessive irrigation, which causes water from underground levels to rise to the surface. When waterlogging occurs, it can result in soil displacement, thereby obstructing the usual air supply that permeates through the soil pores and hindering the growth of vegetation. The restriction of airflow in the soil can cause its oxygen levels to decline and carbon dioxide levels and ethylene levels to increase. Additionally, it leads to crop lodging and contributes to diminished soil conditions. A decrease in photosynthesis and net carbon fixation ultimately results in a decline in both growth and yield of crops [28].

Waterlogging in plants causes oxidative stress due to an elevation in reactive oxygen species, leading to a cascade of harmful events including lipid peroxidation, protein degradation and DNA damage within the cells. Thus, waterlogging alter most of the physiological and biochemical processes in plants [29].

4.3 Nutrient Management to Mitigate Waterlogging Stress

The addition of potassium supplements enhanced the absorption of nutrients in waterlogged plants, leading to a notable increase in the accumulation of potassium, calcium, nitrogen, manganese and iron. Application of potassium (60 kg ha^{-1}) through soil and foliar spray proved to be the most effective method in counteracting the negative impacts of waterlogging in cotton [30].

Seed inoculation or foliar spray of two biofertilizers *viz.*, AAP (*Azotobacter chroococcum, Azospirillum spp.* and *Pseudomonas spp.*) and APB (*Azospirillum spp.*, *Pseudomonas fluorescens* and *Basillus subtilis*) was found to be effective in alleviating the adverse effects of the flooding in *Brassica napus L.* [29]. Application of *Gloeotrichia sp*. (at the rate of 10 kg dry weight ha^{-1}) increased the grain yield by 34.6 per cent over uninoculated condition in rice crop. Dash et al. [31] reported that diazotrophic cyanobacteria (*Aphanothece sp.* and *Gloeotrichia sp*.) are recognized for their ability to fix atmospheric nitrogen in lowland rice fields because they significantly contribute nitrogen, organic carbon and growth- promoting substances which help in building soil/water fertility and microbial flora [31].

5. SALT STRESS

One of the frequently encountered forms of land degradation is the result of soil salinization. Arid and semiarid regions worldwide face a significant issue with salinity, as the amount of evapotranspiration surpasses rainfall, leaving insufficient rainwater to remove soluble salts from the root zone [32].

The presence of an excessive amount of soluble salts that hinder or impact the normal functions of plant growth defines salinity. The measurement is determined by factors such as electrical conductivity (EC), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), and pH. Soils with an EC greater than 4 dSm^{-1}, ESP below 15 percent and pH below 8.5 are classified as saline soils [33]. Saline soils contain a combination of chloride, sulphate, sodium, magnesium and calcium ions, with sodium chloride frequently being the predominant salt.

The presence of salt stress exerts adverse effects on various metabolic processes such as the uptake of nutrients, the process of photosynthesis and the synthesis of proteins and nucleic acids. The adverse effects are manifested by low osmotic potential of soil solution, nutrition imbalance and higher concentration of nutrients in the rhizospheres and ultimately reduce uptake of nutrients by plants [34].

5.1 Nutrient Management to Mitigate Salt Stress

Several methods are currently being implemented to counteract the detrimental consequences of salt on crops. Ion and osmotic balance are crucial for plants to exhibit salt tolerance and uphold intercellular K^+/NH_4^+ equilibrium. The capacity of plants to tolerate salt is enhanced through the regulation of sodium uptake, in which potassium (K) assumes a pivotal function [35].

Tuna and colleagues [36] discovered that the inclusion of calcium (5 mM $CaSO_4$) in the saline nutrient solution (75 mM NaCl) resulted in enhanced shoot and root dry weights, increased calcium concentration and elevated K^+/Na^+ ratios. The key factor in enhancing salt tolerance in plants lies in the reduction of sodium uptake with respect to potassium (K) playing a pivotal role in this process [35].

According to the findings of Tuna et al. [36], the supplementation of calcium in the saline nutrient solution led to notable improvements in shoot and root dry weights, as well as increased calcium concentration and K^+/Na^+ ratios. Enhancement of Ca^{2+}-mediated membrane integrity consistently results in a decrease in K^+ leakage from the root cell, thereby promoting a more advantageous root K^+ status. Due to the foregoing attributes, gypsum and associated S-containing compounds have the ability to improve growth of many crops, including cabbage [37], sugarcane [38], pea [39], rice [40], berseem clover [41], fodder beet [42] and onion [43] grown under salinity stress conditions.

Nitrogen application offers an additional approach to address the limitations imposed by salinity on crop growth. The inclusion of nitrogen in the saline media led to a marked decline in the formation of detrimental oxidative stress biomarkers, namely hydrogen peroxide, lipid peroxidation and electrolyte leakage ratio. The addition of nitrogen also resulted in an increased accumulation of osmolytes, such as soluble sugars, soluble proteins and free amino acids [44].

The application of silicon in the form of silicic acid at 1.5 mM concentration in rice plants plays a crucial role in enhancing their tolerance to salt stress [45]. This is achieved by mitigating the negative impacts of excessive ions and osmotic pressure as well as the regulation of root morphological traits and osmotic potential helps in alleviating osmotic constraint.

The application of organic amendments including farmyard manure (FYM), compost, poultry manure (PM) and mulches enhance soil characteristics, boosts chlorophyll content and improves the K^+/Na^+ ratio, consequently enhancing the soil's ability to withstand salinity [46].

Microorganisms produce various enzymes, including 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which have a crucial impact on alleviating the adverse effects of salinity stress on plants. Ethylene, a vital phytohormone, is indispensable for plants during specific developmental stages like germination and ripening [47]. However, when plants encounter stress, they often experience an excess of these factors, which can negatively impact their growth. This excess leads to leaf abscission and inhibits root elongation, hindering the overall development of the plant. The concentration of ethylene is effectively decreased through the enzymatic action of ACC deaminase, which breaks down ACC, the precursor of ethylene, into ammonium and alpha-keto butyrate, serving as an energy source. [48]. Several species, including *Pseudomonas putida, Arthrobacter protophormiae, Pseudomonas fluorescens, Bacillus subtilis, Burkholderia sp,* contribute to the salinity tolerance of plants [49].

The study conducted by Cordero et al. [50] compared the effect of seven pre-selected bacterial inoculation with a control (without fertilization), named as biological fertilization and chemical fertilization (0.6 g L^{-1} of NPK solution 20: 20 : 20 ratio). After imposing salt stress (100 mM NaCl) all plants produced thicker leaves (lower specific leaf area) to minimize water loss as well as capacity of some strains to keep high K^+ levels in plants was identified to be crucial for keeping hydration and turgor during salt stress. Kaloterakis et al. [51] reported the positive impact of seed inoculation with *Bacillus* species on enhancing plant growth characteristics and nutrient status in cucumber under high salinity.

6. SOIL ACIDITY

Soil acidity poses a significant threat to land degradation. Excessive acidity in the soil leads to a reduction in the accessibility of vital nutrients, intensifies the effects of harmful elements, diminishes plant productivity, disrupts crucial soil biological processes such as nitrogen fixation and renders the soil more susceptible to structural deterioration and erosion. Soil acidity is a consequence of excess amount of H^+ ion and Al^{3+} ion in the soil solution [52].

6.1 Nutrient Management to Mitigate Soil Acidity

Acidic soils poses a challenging environment for the growth of plants. The acidity of the soil significantly hampers the availability of nutrients to plants and disrupts the essential microbial processes responsible for the decomposition of organic matter and nitrogen fixation. Plant roots are greatly affected by the concentration of Al^{3+} in the soil solution in strongly acidic soils (pH < 5.5). The excessive use of fertilizers without the addition of lime is the main factor leading to the formation of highly acidic conditions in soils [53]. The application of dolomite, lime or rice husk ash has demonstrated its efficacy in reducing acidity in extremely acidic soils of Vaikom Kari in the Kuttanad region (acid sulphate soil), leading to an enhancement in rice yield [54]. Customized fertilization with lime, N, P, K, Mg and foliar application of N-P-K:19- 19-19 (1%) at the maximum tillering stage and foliar application of N-P-K:13-0-45 (1%) and Solubor (0.2%) at panicle initiation stage were found to be promising in Orumundakan tracts of Kerala [55]. Geng et al. [56] reported that that application of biochar increased soil pH by 8.48 -79.25 per cent and reduced exchangeable acidity, exchangeable Al and exchangeable H^+ by 56.94–94.95 percent, 34.38–95.66 per cent and 58.72–93.27per cent, respectively.

The application of arbuscular mycorrhizal fungi led to a notable reduction in Al accumulation and effectively countered the detrimental effects of Al on growth and photosynthesis. The mitigating effect of AMF was correlated with the enhancement of proline biosynthesis via the glutamate and ornithine pathways [57]. The application of AMF (*Rhizophagus irregularis*) treatment leads to a substantial enhancement in the fresh mass of barley plants, resulting in a remarkable 73% increase compared to plants treated with Al. Panhwar et al. [58] reported that application of rice husk biochar (RHB) or ground magnesium limestone (GML) with bio-fertilizer, applied at a rate of 4 t ha^{-1}, has the potential to enhance soil biochemical properties as well as the growth of rice on acid sulphate soils was significantly improved as a result of an increase in soil pH (>5.0) and a reduction in Al and Fe levels.

7. METAL TOXICITY

Common toxic effects on plants, including reduced biomass accumulation, chlorosis, growth and photosynthesis inhibition, disrupted water balance and nutrient assimilation and senescence, are typically observed as a result of exposure to excess amount of both essential and non-essential metals. Ultimately, these adverse effects can lead to the death of the plant.

7.1 Fe Toxicity

Iron (Fe) toxicity is a prevalent nutritional disorder that affects wetland rice cultivated in acid sulphate soils, ultisols and sandy soils with a low cation exchange capacity. These soils typically exhibit moderate to high acidity and contain active Fe, which is easily reducible. The detrimental effects of iron toxicity can lead to a significant reduction in rice yields, ranging from 12 to 100 percent [59]. The extent of yield loss depends on the genotype's tolerance to iron toxicity, stress caused by excessive iron and the fertility status of the soil.

Iron toxicity results in elevated levels of polyphenol oxidase activity, which subsequently leads to the synthesis of oxidized polyphenols. Additionally, it induces chlorosis, leaf bronzing, diminished root oxidation capacity, hindered root elongation, stunted growth, severely restricted tillering and the formation of iron plaque on roots of rice crop [60].

7.1.1 Nutrient management to mitigate Fe toxicity

Chalmardi et al. [61] found that the addition of silicon can effectively boost the activity of antioxidant enzymes, such as catalase, ascorbate peroxidase and soluble peroxidase under moderate Fe toxicity. The outcome of this is an enhanced detoxification of hydrogen peroxide and a reduction in lipid peroxidation. Hence, the incorporation of silicon in plant nutrition has the potential to mitigate the adverse impacts of iron toxicity by reducing plant iron levels and enhancing the activity of antioxidant enzymes. The presence of silicon amendment has the capacity to minimize the formation of reddish iron plaque on the surface of epidermal cells of roots and root hairs when exposed to iron toxic conditions [62]. Humic acid, a biochemical compound, exhibits the capacity to bind Fe^{2+} ions and effectively manage the iron concentration in the rhizosphere. Addition of 450 ppm humic acid decreased the Fe^{2+} concentration in the solution at about 418.19 ppm for humic acid from peat soil; 421.27 ppm for humic acid from rice straw compost; 397.58 ppm for humic acid from municipal waste compost and 382.94 ppm for humic acid from manure [63].

7.1.2 Mn toxicity

Mn toxicity frequently manifests in acidic upland soils with a pH below 5.5, often coinciding with the presence of Aluminum (Al) toxicity. Mn toxicity can be identified by the appearance of yellowish brown spots between leaf veins as well as the occurrence of chlorosis in younger leaves. Furthermore, stunted plant growth and reduced tillering are characteristic symptoms of this condition [60].

7.1.3 Nutrient management to mitigate Mn toxicity

Manganese toxicity adversely affects the levels of chlorophyll, carotenoids and net photosynthesis [64]. Silicon effectively enhances Mn toxicity tolerance in rice can be achieved by elevating chlorophyll concentration, improving light-use efficiency, increasing ATP concentration, stabilizing the structure of photo system I and facilitating CO_2 assimilation. Che et al. [65] reported that the presence of silicon in rice crop reduces the rate of Mn translocation from the roots to the shoots. This decrease is likely attributed to the formation of a Si-Mn complex.

7.1.4 Al toxicity

The presence of aluminum toxicity disrupts the plant's ability to absorb, transport and utilize nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), molybdenum (Mo) and boron (B) [66]. The presence of aluminum is associated with restricted root growth, resulting in decreased efficiency in nutrient and water uptake and the potential inhibition of microbial processes. The presence of toxicity can be identified by the occurrence of interveinal chlorosis on the leaves, which is characterized by yellow to white mottling between the veins. This is then followed by the withering of leaf tips, scorching of leaf margins and formation of deformed roots [60].

7.1.5 Nutrient management to mitigate Al toxicity

The presence of silicon alleviates the symptoms associated with Al toxicity including leaf chlorosis and stunted growth of plants [66]. Total chlorophyll and carotenoids were found to be lower in the Al treatment as compared to the control (No Al). However, the application of Si along with Al effectively prevented the decline in chlorophyll content in rice seedlings, while having no impact on carotenoids, unlike the treatment with Al alone [67]. Silicon effectively alleviated Al toxicity in upland rice plants by reducing the transportation of Al to the plant shoots. However, it did not have an impact on the rate at which Al was absorbed by the roots [67].

The characteristics of biochar, including its production process, pyrolysis temperature, pH level, electrical conductivity, cation exchange capacity, calcium carbonate equivalent, cation content (such as Ca, Mg, K, Si, etc.), porosity, ash content, surface area, and the presence of carboxylic and oxygen-containing functional groups, play a significant role in influencing the toxicity of Al in soil [68]. The alkalinity of biochar and the presence of both polar and non-polar surface sites for Al adsorption are crucial factors in mitigating soil aluminum toxicity. As a soil amendment, biochar showcases remarkable potential, while also providing an abundant supply of essential nutrients for plants [69]. Biochar possesses the ability to mitigate soil Al toxicity through various mechanisms. The soil pH increase can be significantly influenced by the interaction between carbonates and oxides produced during the pyrolysis of biochar as well as the presence of monomeric Al species in the soil solution. The biochar contains basic cations that have the ability to substitute the Al ions found in soil exchange sites, resulting in the formation of Al hydroxides with a more neutral nature in the soil [70].

7.2 Heavy Metal Toxicity

Heavy metal stress results in a considerable decline in physiological and biochemical processes and restricts the plants from fully expressing their genetic potential [71]. Heavy metals can naturally experience reduced mobility and bioavailability in soils due to their retention through sorption, precipitation and complexation reactions. The addition of organic amendments and nutrients can expedite the natural attenuation process, also known as natural remediation [72].

7.2.1 Nutrient management to mitigate heavy metal toxicity

The prevalence of inorganic arsenic in rice grains is a matter of global significance, considering that arsenic is a source of this cancer-causing agent in the human diet [73]. In anaerobic paddy soils, arsenite emerges as the predominant form of arsenic, resembling silicic acid, thus rice plants efficiently incorporate it through assimilation. The addition of silicon fertilization in paddy soils led to a significant reduction of 22 percent in arsenic levels found in rice grains [74].

It is widely acknowledged that the utilization of biochar in soil treatment can effectively lower the bioavailability of heavy metal contaminants, thereby mitigating the risk of these substances being absorbed by agricultural crops. The study conducted by O'Connor et al*.* [75] showed that rice straw and wheat straw biochar field trials showed best performance in terms of reduced contaminant leaching potential and enrichment of crop tissue. Miscanthus and wood-based biochar field trials showed best performance in terms of increased crops yields.

The interactions between heavy metals and specific PGPB (Plant Growth Promoting Bacteria) address issues related to metal toxicity and contribute to the promotion of plant growth [76]. The availability of heavy metals are found to reduce in soil after amending with AMF, rock phosphate + AMF addition, mixed microbial culture, rock phosphate + mixed microbial culture, addition of biochar and addition of compost. The compost and mixed microbial culture amended treatments exhibited heavy metal (Cd or Pb) concentrations in the soil below the detection limit for Cd (< 0.01 µg/kg) using ICP-OES analysis [77]. The immobilization of Cd is facilitated by the compost due to its adherence to humic substances and organic functional groups such as carboxyl, carbonyl and phenolic compounds. Simillarly Adeyemi et al*.* [78] found that the concentration of Cu, Pb, and Zn in soybean tissues was significantly affected by the interactions between AMF (*Glomus mosseae*) inoculation and the concentrations of heavy metals.

8. TEMPERATURE STRESS

Temperature stress, both high and low, plays a significant role in influencing the morphology, anatomy, phenology and plant biochemistry [79].

8.1 Nutrient Management to Mitigate High Temperature Stress

High temperature stress leads to the accumulation of reactive oxygen species (ROS), which is a significant factor contributing to the decrease in crop productivity [80]. Nitrogen plays a pivotal role in the tolerance of temperature stress. In elevated temperatures, the level of light intensity is also increased. The combination of high light intensity and high temperature adversely impacts the absorption of mineral nutrients in plants, which impedes plant growth [81]. Among the mineral nutrients, nitrogen holds great significance in facilitating the effective utilization of absorbed light energy and the metabolic pathways associated with photosynthetic carbon metabolism. Tawfik et al*.* [82] reported that some detrimental effects of heat stress on plant growth and stomatal function may be alleviated by Ca and N application during heat stress. According to the data, it is also suggested that the utilization of Ca and N application can help to mitigate heat stress and ensure plant productivity. The results of study conducted by Liu et al. [83] further confirmed that increasing N application could alleviate yield losses caused by high temperatures in super hybrid rice during the flowering stage. Increased N levels could reduce yield loss by bringing about 7.6 per cent increase in number of spikelets per panicle in rice.

Boron possesses the capacity to enhance the antioxidant activities of plants, thereby alleviating the damage caused by reactive oxygen species (ROS) induced by temperature stress. Boron nutrition enhances the transport of sugars within the plant, thereby facilitating seed germination and grain formation. As a result, the yield is improved even when the plant is subjected to high temperature stress [6]. Shahid et al. [84] reported that exogenous application of boron had a substantial effect on cell membrane stability, sugar mobilization, pollen viability and spikelet fertility, hence the yield. Similarly, the results of the study conducted by Calderon-Paez et al*.* [85] showed that, under heat stress conditions foliar application of boric acid (25, 50 or 100mg L^{-1}, respectively) or sodium borate (50mg L^{-1}) significantly increased the net photosynthesis compared to untreated plants (19.7 mmol CO_2 m^{-2} s^{-1} with B 14.4 mmol CO_2 m^{-2} s^{-1}).

8.2 Nutrient Management to Mitigate Low Temperature Stress

The rate of metabolic processes gradually decreases as the temperature decreases and under severe stresses, it may come to a complete halt. Cold temperature stress, ranging from 0 to -10 ^{0}C, exerts a wide range of impacts on the cellular constituents and metabolic pathways of plants. Cold temperature extremes can cause varying levels of stress, which depend on the intensity and duration of the exposure. Numerous studies have shown that the cell's membrane systems are particularly vulnerable to freezing injury in plants. The damage to these membranes is primarily caused by the extreme dehydration that occurs during freezing [86].

Nitrogen application after low-temperature stress enhanced the recovery of rice tillering. Four weeks after nitrogen application, the rice tiller number recovered to 87.90 -92.92 per cent of normal levels under 15 °C and to 70.39–73.85 per cent of normal levels under 12 °C [83]. Nitrogen application at low temperature stress could reduce the damage caused by ROS and help the recovery of rice growth. The presence of calcium is crucial for the occurrence of chilling induced stomatal closure in chilling tolerant genotypes. Stomatal closure is induced by an elevation in the supply of Ca^{2+} and this impact is most noticeable in plants that have been cultivated in low temperature environment [87]. Low night temperature stress led to a decrease in the net photosynthetic rate, effective quantum yield of photosystem II and photochemical quenching. However, the introduction of $CaCl_2$ as a pre-treatment resulted in an improvement in both the photosynthetic rate and quantum yield of photosystem II under the stress caused by low night temperatures [88].

9. CONCLUSION

The biggest challenge in agricultural production is to ensure future food security for the booming population. However, environmental stresses are a significant hurdle in this endeavour. Abiotic stresses being the major environmental stress, affects most of the morpho- anatomical and physiological processes in plants. In general, these stresses affect chlorophyll synthesis, leaf growth, enzyme activity, transpiration, stomatal conductance, membrane stability and eventually affects crop productivity. The global scenario of climate change further increases the detrimental effect of abiotic stress on plants. Though developing variety is an essential step for adapting, proper soil nutrient management strategies can help plants to mitigate abiotic stress tolerance. Nutrients such as nitrogen, potassium, calcium and magnesium increase the concentration of antioxidant enzymes such as superoxide dismutase, peroxidase and catalase, reducing reactive oxygen species. Nutrients such as potassium and calcium help in improving stomatal regulation and osmotic adjustments by improving water uptake. Under temperature stress, these nutrients aid in maintaining a high tissue water potential. Micronutrients such as iron, boron and zinc help in activating various physiological changes in plants like activation of defence mechanisms and improvement of metabolic process by which the plants adapt to various adverse stresses. Thus, nutrient management proves to be an efficient strategy towards climate resilient agriculture for ensuring food security.

10. FUTURE PROSPECTS

Plant nutrition is an effective, low-cost and sustainable way of mitigating abiotic stresses in crop plants. Exploring more efficient soil nutrient management methods involving customized nutrition and precise nutrient combinations can help plants to ameliorate abiotic stress much effectively. Detailed research activates must be taken up to understand the role of nutrients under various stress levels and molecular pathways underlining the same. In the wake of climate change, a better understanding of nutrient interactions, their optimum concentration and phenological stage of application will also equip agriculturists with much efficient methods for management of abiotic stresses.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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