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Abiotic Stress Tolerance in Cotton

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Abstract

Cotton (*Gossypium hirsutum* L.) is a vital fiber crop that is being cultivated under diverse climatic conditions across the globe. The demand for cotton and its by-products is increasing day by day due to more consumption of this fiber in the textile industry and the utilization of cotton seed as a source of edible oil. However, the average seed cotton yield in the world is below that of the potential yield of cultivars. The factors responsible for low yield includes shortage of approved seed, pest and disease attack, weed infestation, unwise use of nutrients, and the incidence of abiotic stresses (including drought, heat, and salinity). Among these, the abiotic stresses are a single major factor, which is responsible for reducing the yield now and will affect the productivity of cotton in future. In this scenario, it is necessary to adopt ways to improve the tolerance of cotton against abiotic stresses. The strategies for improving tolerance against abiotic stresses may include the wise use of macro- and micronutrients, the use of osmoprotectants, the use of arbuscular mycorrhizal fungi, and the plant-growth promoting rhizobacteria.

Keywords: nutrient management, PGPRs, osmolytes, plant hormones, fiber

1. Introduction

Abiotic stresses are major limiting factors that affect the growth, yield, and development of cotton. It is a fiber crop. It is cultivated in many countries across the globe. Medicinal products, home stuff, and cloth products are being processed from cotton crop. The raw material for the textile industry and also human oil consumption requirement are fulfilled by this crop. Extreme temperature, salinity stress, and water depletion are the main abiotic stresses that are considered the primary factors, which limit the productivity of cotton. The worldwide reduction of cotton crop is 50% due to the abiotic stress [1].

For maximum yield of cotton crops, they require optimum growth conditions like other field crops. For example, a temperature of 27–32°C is preferred by cotton crop during the formation of boll. At $\geq 36^\circ\text{C}$ [2], the major reduction in carbon fixation was found in cotton crop, and for optimum photosynthesis, the optimum temperature is $\sim 33^\circ\text{C}$. Poor yield and growth of the plant are caused by the major impact of salinity and alkalinity. The water stress in cotton is caused by salt acting as an osmoticum.

Specific ion toxicity is also a major cause of low yield in this crop. Inequity of nutrients is also a major cause. Plant metabolism is affected by impairing the photosynthetic process and membrane thermostability due to high temperature

management. At the higher temperatures, the protein may be denatured and the activity of enzyme is more sensitive. Due to the effect of drought stress, the cell growth is influenced by the decrease in turgor pressure in cotton crop. The carbohydrate metabolism as well as photosynthesis is influenced by the drought stress directly or indirectly. Any change in carbon uptake also changes the process of photosynthesis resulting in the decrease of boll maintenance of the cotton plant and also the area of leaf that is a response to the stress due to drought [3]. The fiber quality, yield, and growth of this crop are affected by different abiotic stresses. In this chapter, we have discussed the impacts of different abiotic stresses on cotton performance and have enlisted possible improvement in its performance through application of plant hormones (auxin, cytokinins, abscisic acid, brassinosteroids, ethylene, and gibberellins) and plant nutrients (macronutrients and micronutrients).

2. Salinity stress

Throughout the biosphere, the salinity stress has been the most important restrictions for the productivity of agriculture [4]. The cultivated area affected by the stress of salinity all over the world is 20% [5]. Because of decline in water uptake by emerging seeds, plant roots, photosynthesis, respiration, and protein synthesis, germination is reduced due to impact of salt stress. It also affects productivity and growth of the cotton crop [6]. In mitochondria and chloroplast, the undue accumulation and generation of reactive oxygen species [ROS; like superoxide anion (O^{2-}), the hydroxyl radicals (OH), and hydrogen peroxide (H_2O_2)] are a result of the effect of soil salinity stress [7, 8]. Excessive salts in soil affect negatively the productivity and growth of cotton [9]; however, cotton is one of the most salt-tolerant crops. Plants own a number of antioxidant enzymes such ascorbate peroxidase (APX), glutathione reductase (GR), and superoxide dismutase (SOD) for fortification against the damaging effect of ROS (e.g., superoxide anion (O^{2-})) [10]. Under the unfavorable condition, the osmolytes metabolize the function in cotton to produce sugar alcohol [11]. Glycinebetaine and Proline serve as scavengers of ROS and also well-suited protectants, osmolytes for the macromolecules under the condition of salt stress. With specific references to stress and photosynthesis metabolism for controlling the survival and productivity, little information is present on biochemical and physiological features of cotton under the salt stress conditions. At the persistent salinity of 17 dS m^{-1} , the yield reduction is 50%, and when the salinity is at threshold level, which is 7.7 dS m^{-1} , a notable decline in seed cotton yield occurs. In conclusion, soil salinity negatively impacts the cotton growth and yield by affecting the plant physiological and biochemical traits.

3. Drought stress

For all the agricultural commodities, the availability of water is a determining factor for the yield and growth of the cotton plants under stress situations. Increasing human demand for water availability and demands for water for agriculture purpose in increasing and changing climate condition are the main factors restraining accessibility to water for agriculture. The shorter plants with small number of nodes resulted due to the drought stress in the cotton plants during the squaring period. With the help of drought stress treatments, there would be highest yields of the cotton plants. Except the full application of irrigation, the fiber quality parameters were significantly improved. The poor fiber quality, lowest fruit retention, and lowest yield production at the flowering stages are more sensitive to

drought stress. There is poor fiber quality and yield losses at the squaring as a result of stress due to drought [12]. The severity and timing of the drought determine what will be the effect of water stress on yield. Photosynthesis process is slowed down because of a decrease in the number and size of cotton leaves. Krieg [13] showed that water stress reduced crop growth rate.

The variability in genotype responses to drought stress in cotton has been reported [14]. Compared to drought tolerance, many morpho-physiological characters have been recommended as significant selection criteria for cotton crops. The distance from the first main lateral root to transition zone is increased due to drought stress in cotton, and also the increase in taproot weight, seedling vigor, the amount of lateral roots, and also the development of root system is rapid [15]. The temperature of canopy, the discrimination of carbon isotope, leaf water content, conductance of stomata, and rate of photosynthesis also reduce the rate of transpiration due to the effect of drought [16]. Cotton crop has taproot system. In cotton seedlings, a number of lateral roots are produced, which depends on the xylem poles for water absorption [17]. The amount of vascular bundles increases due to the increase of branching intensities of lateral roots in the cotton crop [18]. In cotton, decreasing leaf transpiration by stomatal transpiration (TR_{st}) and cuticular transpiration (TR_{cu}) is the important physiological indicator of water stress [19].

Stomatal conductance controls stomatal transpiration (TR_{st}) under water stress conditions. Leaf surface characters like morphological structure and the thickness of the wax layer affect the cuticular transpiration (TR_{cu}) [20]. Lewitt showed that stomatal closing can avoid drought in plants. Stomatal closing and opening are regulated by the help of guard cells. Overproduction of reactive oxygen species (e.g., superoxide and peroxide) is followed by drought stress. Inhibition of photosynthesis and cellular damage are a result of this. This process is known as oxidative stress and is a major cause of plant damage due to stresses of environment [21] in many crops. According to McMichael et al. [17], in the present cotton cultivars, genetic variability is low for many drought-tolerant characters. So, under high rainfall and humid situations, much of the current cultivars are opted. Potential sources of traits associated with drought tolerance are considered as primitive race stocks of upland cotton [22].

4. Heat stress

By virtue of its geographical position, the cotton belt of Pakistan is present in the area of high level of temperature. In the Kharif season, the temperature approaches 50°C. The water stress and high temperature increase the impact that reduces the yield or quality of fiber, and fewer plants per unit area are a result of the heat stress with the other environmental stresses [23]. It is estimated that the harmful effect of heat stress causes the cotton crop to achieve only about 25% of yield potential [24]. The effect of these stresses is location-specific, exhibiting variation in frequency, intensity, and duration. The environmental stresses are site-specific, exhibiting frequency variation, light intensity, and duration of light. It is the practical approach to estimate the responses of heat responses by field evaluation of cotton under high temperatures with appropriate irrigations [10]. The ability to screen for heat tolerance might be affected by the timing of heat stress. It has been suggested that the identification of relative cell injury level from leaf disks at high temperature is the screening technique for heat tolerance in plants [25]. Plant development rate is much increased at high temperature, which reduces the life period besides other detrimental effects like denaturing of membranous structures [26]. Lint yields and quality are negatively correlated with the high temperature [27, 28]. The first and foremost requirement is to identify the suitable stock(s) to be used in breeding in

any crop improvement program [29]. It was reported that in most dry land cotton production areas seedling heat tolerance is essential. Under heat conditions, emerging cotton seedlings poorly develop root system and show burning effects on the leaves; particularly, the younger leaves are adversely affected [11]. When plants grown in pots are exposed to high air temperatures, the shoots and the roots are challenged with hot condition, and it was observed that optimum temperature for leaf area development was 26°C for cotton [30].

5. Waterlogging stress

In areas with poor drainage or level, due to the excess of drainage and rainfall, the soil surface becomes saturated with water and this state of land is called waterlogging. Every year, the land area of the world experienced by waterlogging is about 10% [31]. The following are the two conditions: one is anoxic (oxygen absent: energy gain by fermentation is the only condition) and the other is hypoxic (low oxygen concentration: mitochondrial respiration is reduced and the process of fermentation takes place) because the microbial activity and plant activity use maximum amount of oxygen. During the conditions when the soil is waterlogged, the physicochemical properties such as the redox potential and pH are strongly changed due to the lack of oxygen concentration [32]. The effect of waterlogging on the salt-containing soil is more than 50% and these soils are mostly used for high-value crops such as cotton [33]. There are many drawbacks of the consequences of waterlogging for the plants of cotton, which may include terminated growth and the death of root apices, and also, increasing nutrient patterns may also be changed. For the growth of cotton, a waterlogged environment is lethal because it stops exchanging of gas and also results in energy problems [34]. Through the process of waterlogging, yield formation and the growth of cotton are strongly affected. But also these processes are complicated and remain unclear. It is reported that the adoption of cotton to the waterlogged stress is very poor [35]. But the cotton crop is that type of species that has indeterminate growth habit and has the large ability to compensate after the effect of abiotic stress.

6. Improving abiotic stress tolerance in cotton

6.1 Plant hormones

6.1.1 Auxins

For the development of the body and for the life cycle of plants, auxins are essential. These hormones play a critical role in the coordination of behavioral process and also in the growth of the plant. These hormones are present in all parts of plants. For the different process, the amount of these hormones is also different; for example, the most dominating and effective auxin is indole acetic acid (IAA). For the growth of cotton plants in abiotic stress, the dynamic and environment-responsive pattern of this hormone distribution within the plants of cotton is a key factor for their growth. These are also very important for the development of plant organs such as leaves or flowers and for the environmental reaction under the abiotic stress. Through the plant body, the process of polar auxin transport is achieved by the complex and well-coordinated active movement of these hormones from cell to cell in the plant body. Indole-3-propionic acid, indole-3-butyric acid, phenylacetic acid, indole-3-acetic acid, and 4-chloroindole-3-acetic acid are the five naturally occurring auxins, which are endogenous in nature [36]. For the proper development of plant growth, these hormones are

very essential and contribute to giving the shape to the organ. Plants would be merely successful heaps of similar cells without hormonal regulation and organization of auxin hormone. The development of primary growth poles and future buds are formed by the auxin application. The employment of auxin begins in the embryo of the plant, and for subsequent growth, the distribution of the hormone is directional under the abiotic stresses [37]. This hormone is very important for proper growth and development. Also, with the help of this hormone, fruit senescence is delayed. In cotton, auxin plays a small role in initiation of the flowering and for reproductive organ development. Under the abiotic stress condition, when there is low concentration of auxin hormone, the senescence of the flower is delayed. In cotton, the lower concentration of this hormone can inhibit the formation of ethylene and also higher concentration can disturb the synthesis of ethylene. In cotton plants under abiotic stress, the auxin hormone influences a different kind of process such as the developmental and physiological. Through the auxin hormone application under stress conditions, rapid alteration in the roots of cotton occurs. Under abiotic stresses, in the cotton plants, various signaling auxin components appear that mediate diverse physiological and developmental processes. The target of various auxin-signaling components might be the strategy of potential to enhance the tolerance in cotton plants under abiotic stresses.

6.1.2 Cytokinins

Cytokinins are naturally occurring type of plant hormones. Under the drought condition, with the help of that hormone, the production of cotton is increased under stress. This increases the cell division and growth. The growth of the plant's main stem and branches is motivated in cotton by these hormones. For the growth and yield of cotton, there are many commercially produced hormones available, which are applied under the stress condition. In the area where there is absence of water or no irrigation, through the application of these hormones, the growth is also improved under stress conditions. Half of the production of cotton from Asia is in arid high water-shortage areas. The 60–65% of the acreage in the area is dry and depends on the rainfall for the moisture of the soil in short growing season. There is more difficulty for the cotton plants to absorb the soil water because the young cotton plant seedlings have small root systems under stress conditions. In the young plant, the defense for the water is promoted by that hormone. Also for the absorption of the soil moisture, it helps to promote the plants to build a strong and deep root system. To prevent the loss of water under stress conditions, it stimulates the growth of protective wax on the surface of the plants. Under water-stressed conditions, it has been reported that the application of cytokinins increases the yield by 5–10%. The cytokinins can be applied in the early season when conducting normal weed management practices, and no extra work is involved for the grower. It should be applied at a relatively low concentration to cotton seeds or to cotton plants at an early stage of development. The developmental and various physiological processes in the cotton plants are done by cytokinins. The division of the cell in plants also increases under the abiotic stress [38].

Cytokinins have a vital function in seed and root development. This hormone also retarded fiber elongation at elevated concentration in ovule culture. Cotton fiber and seed yield were improved by slightly raising the level of endogenous cytokinins. This also decreases the expression of cytokinin dehydrogenase [39]. Plant hormones play a significant role during interaction with physiological and developmental 'switches' involved in fiber growth. Cytokines also help in cell elongation by loosening the cell wall and supplying structural materials under stress conditions. During this process, secondary cell wall deposition and increased cellulose formation are key roles of that hormone. The opposed effect of some hormones may act as a restraining factor for fiber cell development under the abiotic stress conditions. The exogenous application

of plant growth regulators at a particular time may be helpful for the appropriate cell development. Little is known about how some of the cells are differentiated into lint (long fibers) and others into fuzz (short fibers) from the same ovule epidermis. Selective utilization of nutrients for elongation of long fibers is the main reason under the stress. When a number of cells differentiate into fiber, some substances from ovule epidermal cells are transferred into fuzz, which affects other cells to develop into full-length fibers, which is another important reason under the stress condition.

6.1.3 Abscisic acid

The role of the abscisic acid (ABA) in the fiber development is an inhibitor. The growth of the fiber is also decreased when using the ABA to unfertilized cultured ovules [40]. The inhibitory function of ABA is somewhat balanced in the presence of cytokinins, which inhibits fiber development in the absence of ABA. At the time of boll formation, the concentration of ABA is low and also decreases during the next 2 days [41].

It was found that the ABA level was higher in mature cotton fruits as compared to young healthy fruits [42]. It was concluded that the internal ABA level exhibited a reverse correlation with the rate of fiber elongation. Among the different cotton cultivars, it is shown that high internal ABA contents result in shorter fiber and the reverse relationship exists between ABA contents and fiber length. Dasani and Thaker [43] tested the fiber of different cultivars of cotton under stress condition. The function of the ABA is revealed in both in vitro and in vivo situations for the improvement of fiber. The inhibitory effect of ABA on fiber length was reduced due to the addition of growth promoters like naphthaleneacetic acid (NAA) and gibberellic acid (GA) along with ABA. From the results of in vivo and in vitro experiments, it can be concluded that ABA may be playing an inhibitory role in fiber elongation and is a positive indicator of the onset of cell wall thickening.

6.1.4 Brassinosteroids

Brassinosteroids are naturally occurring hormones with steroid chemistry and are found throughout the kingdom Plantae. They elicit growth stimulation at nanomolar concentrations. Brassinosteroids enhance cell elongation and affect cytoskeleton and cell wall structure.

It is stated that adding a minute concentration of brassinosteroid (brassinolide (BL)) to cultured cotton ovules increased cotton fiber elongation, while the use of brassinazole 2001 (BRZ) and also the inhibitor of BR biosynthesis retarded fiber length and ovule size [44]. The application of BR biosynthesis inhibitor (brassinazole 2001) hindered fiber initiation probably due to alteration in the differentiation of ovule epidermal cells into fibers. The exogenous application of BL increases the formation of fiber, while the application of BRZ reverses the effect [45]. BR signal transduction plays a role in determining cotton fiber length. Transgenic plants with altered brassinosteroid insensitive 1 (BRI1) expression produce fibers similar in length to wild-type plants. The thicker secondary wall with fiber is produced by the plants that overexpress BRI1. These are the changes in fiber cell growth correlated with changing in expression of cellulose formation gene in fiber development.

6.1.5 Ethylene

Ethylene biosynthesis is the most important pathway that is upregulated during cotton fiber cell elongation in accordance with recent physiology and gene expression analysis [46] under optimal and suboptimal conditions. During the 10–15 DPA

(days post anthesis), the involvement of 1-aminocyclopropane-1-carboxylic acid oxidase 1–3 (ACO1–3) was predicted very effective for fiber growth elongation under the abiotic stress condition. The exogenous application of the ethylene inhibitor, 2-aminoethoxyvinyl glycine (AVG), inhibits the growth of fiber, and ethylene increased fiber cell expansion under the stress condition [45]. According to the results, under the stress condition, this hormone has a significant role in supporting cotton fiber growth and elongation. Additionally, ethylene might enhance cell elongation by escalating the expression of tubulin, sucrose synthase, and expansion genes [46]. Detection of ethylene in fibers proved that it affects fiber elongation.

Ethylene biosynthesis genes (ACO1–3) are expressed at fiber elongation stage. According to that, it may interact with BR and ROS signaling pathway. Experiments on cultured ovules have shown that exogenous application of ethylene ameliorate the problem of fiber elongation caused due to BR biosynthesis inhibition. The exogenous application of both ethylene and BR on cultured ovules triggered the expression of genes for biosynthesis of other phytohormones. This cross-talk between hormones and genes may regulate fiber development in both negative and positive perspectives [47].

6.1.6 Gibberellins

The combination of auxin and gibberellins has been found to increase the fiber growth in in vitro cultured ovules [48]. Under abiotic stress, the application of auxin and gibberellins from exogenous source is vital for fiber growth in unfertilized ovules [49]. Studies on gene expression also explored the role of gibberellins and auxin in fiber growth. In DNA microarray, a cupin super family protein was found to be upregulated in 10 DPA ovules [50]. Because the plants have tissue sensitivity to improve the crop yield and quality, the transgenic approach has increased the manipulation of the hormones' concentration [51]. At a molecular level, to improve the fiber length and micronaire value, much effort has been made by scientists. Also the increased fiber for lint percentage and elongation was observed in cotton crop [52]. The targeted expression of an IAA biosynthetic gene under floral binding protein promoter (FBP7) was also shown in several studies and amplified the endogenous IAA levels at the fiber initiation stage under the abiotic stress [53]. The main aim of cotton-producing countries is to improve the yield of crop. By developing the seed that gives more yield of fiber under abiotic stress conditions, this aim of high yield can be fulfilled. The development of plant hormones plays an important role for the maximum growth and development of the crop [54]. The exogenous application of GA₃ not only promotes the fiber length but also enhances the thickness of cell wall significantly. During abiotic stress, long length cotton fibers with thicker cell wall and increased dry weight per unit cell length were obtained.

6.2 Plant nutrients

6.2.1 Macronutrients

6.2.1.1 Nitrogen

Nitrogen is a significant constituent of nucleic acids and amino acids and is required in high concentrations to plants. Maximum yields are not obtained from optimum nitrogen supply in the absence of adequate water, and optimum water supply will also not give maximum yield in the absence of adequate nitrogen supply [55]. Cotton that grows in different moisture stress levels in sandy soil shows similar special interactive effects of nitrogen supply and drought stress. Nitrogen shows

genetic variation, selection, and breeding of lineages that are more effective in their N uptake. It is the more efficient strategy in arid land than in temperate zone [56]. When salinity is not severe, the addition of nitrogen enhances the growth and yield of crops [57].

Nitrogen also plays a key role in the synthesis of chlorophyll and proteins as well as in cell division. But cotton production can also be improved by foliar application in salinity stress [58]. Root development, germination, senescence, respiration, cell death, disease resistance, and hormone responses in crops are also influenced by nitrogen application. During abiotic stress in cotton, nitrogen plays an important role to activate the antioxidant defense in cotton [59]. Therefore, when the supply of nitrogen is adequate, root restriction increases the root activity. It also increases the availability of photoassimilates to above-ground plant parts. Hence, with the application of nitrogen to cotton, shoot growth and the ratio of shoot and root are enhanced.

6.2.1.2 Phosphorus

Phosphorus (P) is an essential component of nucleic acids, phosphor-lipids, and adenosine triphosphate. It also plays an important role in the storage, energy transfer, and also transport of carbohydrate. The pH is high and soils are calcareous in arid areas. Under the drought stress condition, phosphorous application can improve the growth of cotton crop [13]. The foliar application of urea and diammonium phosphate is the main source of phosphorous for the improvement of growth and development of cotton crop [60–62]. Improvement of fiber in cotton crop under the stress conditions can be obtained by the foliar spray of phosphorous at the boll formation stage [63]. In addition, boll weight and seed cotton yield are increased under stress [64].

Phosphorous is constituent of cell nuclei, and it is essential for cell division and development of meristematic tissues [65]. Phosphorous also influences the formation of nucleic acid, protein, and lipids as well as photosynthesis. In biotic stress conditions, the application of phosphorous improves the quality parameters of cotton. Cotton shows positive and economical response to phosphorous application [66]. Hence, plant height, shoots, and roots in cotton plants in abiotic stress conditions are enhanced by the application of phosphorous.

Phosphorous is efficiently applied to soil by fertigation as compared to broadcast application. However, in abiotic stress conditions, cotton yield can be improved with adequate amount of phosphorous fertilizer application at appropriate time. The reduced canopy is the result of the unbalanced nutrients in soil from the improper input of nutrients. Therefore, under abiotic stress conditions, photosynthesis rate and the yield of the cotton are reduced [67].

In abiotic stress conditions, the rate of leaf expansion and photosynthesis per unit leaf area of cotton crop are reduced due to phosphorous deficiency [68]. Crop growth, nitrogen and potassium uptake, total chlorophyll content, and dry matter yield of cotton plant are significantly enhanced by phosphorous [69]. The application of phosphorous leads to increased phosphorous uptake and content in leaf, stem, and reproductive parts such as seeds [70]. Phosphorous has a stimulating effect on number of flower buds and bolls per plant as well as is essential for cell division. Plant height, number of sympodial branches, seed index, boll weight, and seed cotton yield vary in all cotton cultivars due to genotypic variation [71, 72].

Cotton is facing decline in yield and quality because of abiotic stresses. Several genes for genetic engineering have been made from the cloning technology such as those related to fiber development (cytokinin dehydrogenase), disease resistance

(PR-3 and PR-10), and stress responses (GbRLI)³. These genes play an important role in successfully generating transgenic cotton lines with greater abiotic stress tolerance [73].

6.2.1.3 Calcium

Calcium plays a vital role in maintaining the many physiological processes that impact both the growth of cotton plants and also the responses to environmental stress. All the biotic and abiotic stresses and damages are repaired and act as defense for the cotton plants by the processes of translocation and respiratory metabolism. Concentration of water and the movement of the solutes influence these processes. These processes are also influenced by the Ca^{2+} on the structure of membrane and on the function of stomata. The uptake of calcium is minimized under stress conditions as compared to other elements. Hence, the accumulation of calcium is decreased to small extent as compared to phosphorous and potassium and this accumulation was in the range of 40, 71, and 91% for phosphorous, potassium, and calcium, respectively, in dry conditions in the mature cotton crops. The direct application of calcium is an efficient method for increasing the fiber yield of cotton. The incidence of fungal pathogens is reduced leading to increase in yield, and several physiological disorders are minimized by the application of calcium salt.

6.2.1.4 Potassium

The optimal supply and the good source of potassium (K) are very critical for increasing the growth and yield of the cotton crop. With the help of stomatal cell, the turgor pressure and osmotic pressure are increased with the help of K under the drought stress condition [74]. Soil salinity problem widely affects all the agronomic and physiological parameters of the cotton crop. These effects were lowered by the optimal application of potassium fertilizers [75]. Potassium increases the uptake of other essential nutrients, so the productivity of cotton is badly affected through the low application of potassium [76]. With no application of potassium, the cotton yield and also yield-contributing factors and fiber quality will reduce [77]. It was suggested in a study that under drought stress, the application of potassium influences the physiological functions of cotton [78]. The two cultivars of cotton were planted in drought stress and well-watered conditions with three potassium rates (0, 150, and 300 K_2O kg/ha) and these plants were showing higher leaf water potential, stomatal conductance, photosynthesis rate, and the maximum and actual quantum yield of PSII. With the application of potassium, the cotton plants were showing lower lipid peroxidation, higher antioxidant enzyme activity, as well as increased proline accumulation as compared to nonapplication of potassium, and a significant relationship was observed between photosynthetic recovery and potassium application.

Maintaining surplus water pressure within the boll also decreases the incidence of disease and improves the water use efficiency and fiber quality with the application of potassium [79]. Potassium application in cotton is also believed to extend the absorption of nitrogen, which causes vigorous vegetative growth and seed cotton yield. Also, the use of potassium in cotton enhanced the metabolic activity and improved the staple length, tensile strength, and fiber length and decreased the amount of damaged fiber [14]. Several other studies have reported an improvement in yield of cotton seed and quality of fiber due to potassium input in cotton under optimal and suboptimal conditions [80–82]. Combined foliar application of magnesium in combination with potassium and nitrogen improved the seed cotton

yield, fiber quality, leaf nitrogen, potassium and magnesium concentration, and water use efficiency of cotton. The improvement in fiber quality was also visible through improvement in fiber strength, staple length, and fiber uniformity index owing to combined foliar application of magnesium in combination with potassium and nitrogen in abiotic stress in cotton crops [83].

Potassium plays a role in maintaining nitrogen metabolism and osmotic adjustment to sustain growth in soil under drought conditions [78]. Cotton plants under drought stress with potassium application not only showed higher osmotic adjustment with accumulation of osmolytes as well as maintaining higher enzyme activity, soluble proteins, and chlorophyll content but also regulate the nitrogen metabolism as compared to the plants without K application [84].

6.2.1.5 Micronutrients

As the cropping intensity increases, magnesium (Mg) deficiency occurs more frequently. Deficiency symptoms of sulfur are associated with the decrease in atmospheric sulfur. The uptake of magnesium and sulfur nutrients is reduced in cotton crop under drought stress. It has severe consequences for S nutrition and crop production. The plants uptake micronutrients through the process of diffusion decline because there is low soil moisture [85]. Cotton crop needs smaller quantities of micronutrients. Therefore, the effect of drought stress on micronutrients (Mg and S) is not the same as for macronutrients (P and N). Due to drought stress, deficiency of boron occurs in cotton crop. Due to the accumulation of silicon under drought conditions, the growth of cotton is improved and silicon is accumulated due to the reduction in transpiration rate [86, 87]. The main factors of saline and sodic soil on which they depend for availability of micronutrients are solubility of the micronutrients, pH, and the nature of the binding sites on the organic- and inorganic-particle surfaces. Salinity stress also affects the concentration of micronutrients in cotton plants, and soil salinity levels are also influenced by the salinity stress [88]. Inorganic nutrients play a significant role in determining plants' resistance to drought or salinity. Hence, both growth and development of cotton plants are similarly influenced by drought and salinity.

7. Use of osmoprotectants

The accumulation of organic osmolytes has been reported in many plants under abiotic stresses. These include polyhydroxylic compounds and zwitterionic alkyl amines. The accumulation of osmolytes is widely discussed nowadays especially in cotton crops [89, 90].

Osmotically active solute is completed by the entry of water into the cell. This water provides sufficient concentrations for turgor pressure, which is necessary for the expansion of cells.

Cotton plants remain fit under stressful environmental conditions due to osmotic adjustment [91]. Therefore, high concentrations of several but not all compatible solutes protect the crop from oxidative damage. Their damage is reduced by scavenging free radicals in addition to their roles in preservation of osmotic equilibrium without disturbing macromolecule solvent relations.

The resistance against the oxidative stress of cotton has recently increased with the action of chloroplast accumulation of mannitol as well as consistent with high diffusion rate limited reactivity of hydroxyl radicals toward the most metabolic intermediates [92]. A significant role is played by the compatible solutes

in terminating free radical chain reaction. The stress tolerance appears due to the critical element glycinebetaine in the cotton plants.

The growth of cotton plants is strongly influenced by the drought and saline environments with the osmoprotectants. Osmoprotectants are enormously proficient compatible solutes. The accumulation of glycinebetaine is induced and improves the tolerance to abiotic stress conditions [93]. The treatment of cotton seeds with the external application of glycinebetaine at increased the cotton seed yield by 18 and 22%, respectively. The growth and survival of extensive varieties of plants such as cotton crops are improved by the exogenous application of glycinebetaine.

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