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REVIEW ARTICLE

Agronomic interventions to enhance abiotic stress resilience in cotton

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Abstract

Cotton, a major fibre and oilseed crop, is highly vulnerable to abiotic stresses such as salinity, waterlogging, heat and drought, which significantly reduce yield and quality. Drought stress alone accounts for approximately 49 % of global agricultural yield losses, while salinity and waterlogging contribute up to 60 % of losses in upland cotton production. This review explores the physiological and biochemical responses of cotton to key abiotic stresses, including salinity, waterlogging, drought and heat. Salinity disrupts plant physiology by inducing ion toxicity and resulting in nutrient imbalances. Waterlogging interferes with photosynthesis and alters metabolic pathways, whereas drought severely affects stomatal conductance and photosynthesis. High temperatures reduce growth and fibre quality. While biotechnological interventions such as the development of salt-tolerant and waterlogging-resistant varieties offer long-term solutions, agronomic practices provide immediate, cost-effective methods for mitigating stress. The agronomic measures discussed include the use of biostimulants, plastic mulching, seed priming, nanoparticles and nutrient management. Biostimulants enhance nutrient uptake and stress tolerance, plastic mulching enhances water retention and moderates canopy temperature and seed priming induces stress resistance by modifying physiological responses. Nutrient management, particularly with respect to nitrogen and potassium, helps maintain plant vitality under stress conditions. This review also highlights emerging trends such as nanoparticle application for stress alleviation and nitrate use for waterlogging mitigation. These agronomic strategies, combined with biotechnological advancements, offer a holistic approach to enhancing abiotic stress tolerance in cotton. However, further research is needed to optimize these practices, especially in terms of addressing environmental challenges such as plastic pollution from mulching and long-term soil health impacts

Keywords: abiotic stress; biostimulants; cotton; drought stress; heat stress; salinity tolerance; waterlogging

Introduction

Abiotic stresses such as drought, heat, salinity and waterlogging are among the major factors limiting agricultural productivity across many countries worldwide. Drought stress accounts for approximately 49 % of the reduction in agricultural yield (1) (Fig. 1). Cotton, one of the most important cash crops globally, supports the livelihoods of millions of farmers and serves as a vital raw material for the textile industry. However, cotton is highly susceptible to various abiotic stresses, including drought, heat, salinity and waterlogging, which significantly affect its growth and productivity. For example, drought stress reduces cotton yield by 30 % (2). Drought and salinity impose greater than 50 % yield reductions on upland cotton (3). Waterlogging has been reported to reduce cotton yields by an average of approximately 60 % (4). Since cotton is a major crop used for both the production of textiles and as a source of edible oil, these yield losses have significant effects on the global economy.

Although cotton is tolerant to salinity with a threshold of 7.7 dSm^{-1}, cotton crops in the early stages are highly sensitive to salinity (5). Salinity induces physiological and biochemical disruptions, leading to delayed flowering, reduced fruit set and lowered boll weight (4). Exposure to high temperatures alters several morphological traits, including plant height, boll number, boll retention, yield components and fibre quality (6). In contrast, drought primarily affects stomatal conductance and photosynthesis. The severity of waterlogging varies with growth stage, with flowering being the most sensitive, followed by the squaring, seeding and boll opening stages

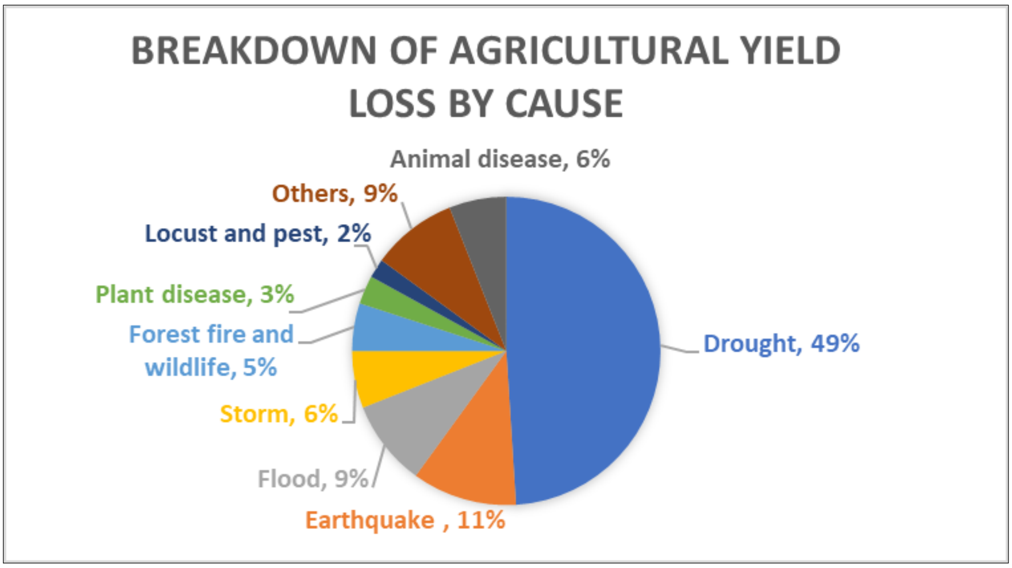

Fig. 1. Major contributors to agricultural yield loss.

(7). The development of abiotic stress tolerance in cotton is crucial for ensuring stable yields and fibre quality, as the crop is increasingly challenged by climate change. Many biotechnological interventions have been proposed for to genetically enhance cotton's tolerance to abiotic stress. In fact, such techniques are highly time consuming and may not immediately solve the challenges faced by cotton producers. In contrast, agronomic practices provide practical, cost-effective methods for overcoming these abiotic stresses and optimizing cotton production. Agronomic interventions can include the use of biostimulants, plastic mulching, seed priming, furrow seeding and nutrient management.

This review explores the major abiotic stresses affecting cotton and examines agronomic strategies to enhance stress tolerance. This study will critically analyse current agronomic practices proven to mitigate abiotic stress. Furthermore, this review also discusses some emergent trends such as the use of nanoparticles for the enhancement of abiotic stress tolerance. Agronomic practices combined with modern technologies, offer a promising pathway to address the challenges posed by the climate change which ultimately leads to an increased incidence of abiotic stress in the production of cotton.

Different types of abiotic stress and the mechanism of stress response in cotton crop

Salinity

Salinity stress often poses a significant threat to global agricultural productivity, as it has several impacts on plant growth, development and survival. In India, approximately 6.7 million hectares of land or 2.1 % of the geographical area are impacted by salinity (8). By 2050, the area of salt affected land may increase to 16 million hectares due to improper irrigation practices and climate change, exacerbating the issue (9). Stress induces ion toxicity, a reduction in water intake, nutrient imbalances and oxidative damage in plants. When the salinity of soil increases, it leads to poor plant performance and decreases microbial activity due to osmotic stress and toxic ion accumulation (10). The presence of excessive salts in the soil directly reduces crop yields and disrupts various physiological and metabolic processes (11). Salinity stress can reduce yields to just 20-50 % of their potential. The critical growth stages of cotton are more vulnerable to salinity stress, such as germination, flowering and boll formation. It reduces cotton growth parameters, proline accumulation, chlorophyll content, photosynthetic rates and stomatal conductance. However, the salt tolerant cultivar CCRI - 79 exhibited better protection mechanism.

Mechanism of the salinity stress response

The principal mechanism of salt tolerance in cotton involves salt extrusion or the compartmentalization of sodium ions (12). The salt tolerant genotypes present a higher ability to compartmentalize ions and leaf glandular trichomes aid in ion secretion (13). Maintaining high K^+/Na^+ and Ca^{2+}/Na^+ ratio in plant tissues is crucial for salt tolerance (14). The accumulation of compatible solutes such as proline, glucose and amino acids, helps maintain water potential and enhances salt tolerance.

The defence system of salt tolerance in cotton involves antioxidants and an active ascorbate-glutathione cycle (14). These antioxidants protect cytoplasmic membranes from oxidative damage and the synthesis of organic solutes such as proline aids in osmotic adjustment (15). Furthermore, the salt overly sensitive (SOS) signalling pathways and alternative splicing mechanisms have been identified as part of the response to salt stress (16). Several genes such as *GhERF2, GhMPK2, GhCIPK6* and *GhNHX1,* are highly expressed in salt tolerant genotypes, especially in the roots (17).

Waterlogging

Waterlogging lowers the availability of oxygen to plants and thus negatively impacts them. It interferes with energy metabolism. Therefore, the direct decline in yield in cotton is due to decrease in photosynthesis (18). The effects of waterlogging on cotton are depicted in Fig. 2. Stress also interferes with the chemistry of carbon and nitrogen in cotton plants, significantly altering soluble sugar and protein contents. A previous study revealed that, within eight days of waterlogged conditions during critical stages such as flowering and boll setting, the levels of soluble proteins and sugar content decrease (19). The percentage

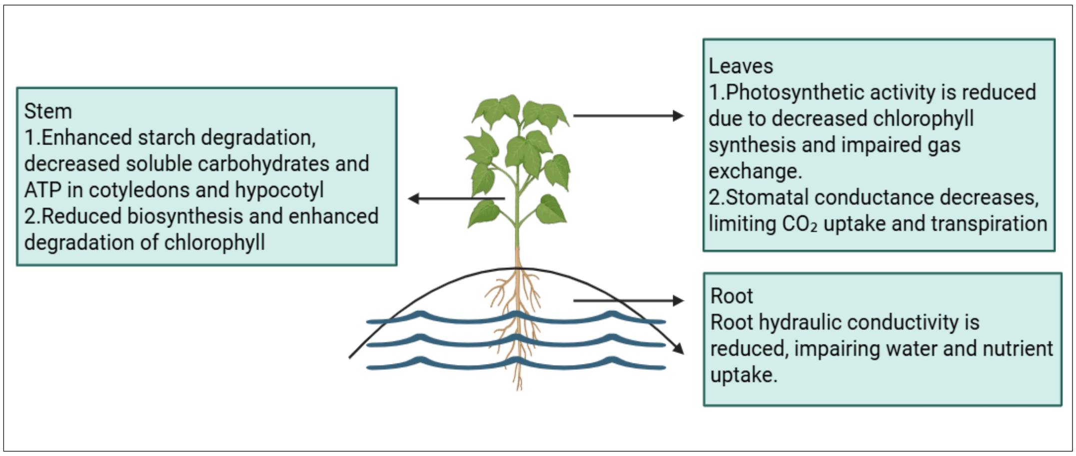

Fig. 2. Impact of waterlogging on cotton growth and physiology.

of yield reduction that occurred in cotton during different growth stages due to waterlogging is shown in Fig 3. Under anaerobic conditions, plants induce the expression of proteins adapted to low oxygen environments and shift metabolic processes to more energy conserving pathways. One of the more insidious effects of waterlogging is the accumulation of malondialdehyde (MDA) in plant tissues. Waterlogging stress significantly increases MDA content in cotton, with reported rises ranging from 12.8 % to 93.1 % compared to non-stressed controls, indicating progressive lipid peroxidation and membrane damage under prolonged stress. Moreover, waterlogging also results in nutrient imbalances, reducing the nitrogen, potassium and calcium levels in the roots, stems and leaves of cotton, but increasing the levels of manganese, iron and magnesium to further hinder plant physiology and constrain the potential for recovery. The plants may form aerenchyma tissues and adventitious roots to improve oxygen uptake as a survival mechanism (20).

Mechanism of response to waterlogging

Cotton responds to waterlogging via three main mechanisms: escape, quiescence and self-regulation or compensation (21). Plants promote the growth of adventitious roots and develop aerenchyma by creating air filled spaces in tissues. In addition, the activities of glycolytic and fermentation enzymes increase to maintain the life of the plant during low oxygen conditions (22). Quiescence involves a reduction in biomass and conservation of energy at the time of submergence. The escape mechanism promotes a high rate of stem extension which makes it possible to reach the air when submerged (23).

Under waterlogging, the synthesis, transport and metabolism of cotton hormones are also impaired. Higher ABA levels in waterlogged cotton plants were recorded in a pot experiment, as well as were lower levels of Indole-3-acetic acid (IAA), Zeatin Riboside (ZR) and Gibberellic Acid (GA) and Gibberellic Acid (GA)/Abscisic Acid (ABA), IAA/ABA and ZR/ABA ratios in waterlogged field conditions (24). A gene expression study revealed that genes responsible for glycolysis, fermentation and mitochondrial electron transport chains were upregulated. Genes related to cell wall synthesis, carbohydrate metabolism, nitrogen metabolism, photosynthesis and amino acid synthesis, especially the aspartic acid and serine-glycine-cysteine pathways were downregulated (25). Other signalling molecules include NO and H_2O_2 play critical roles in interaction between cotton and waterlogged water. The feature indeterminate growth habit and the ability to compensate for stress through growth recovery contribute to plant tolerance to waterlogging. Following 10 days of recovery after waterlogging stress, dry matter accumulation in cotton showed significant rebound by 28.6 %, 70.9 % and 29.0 % during the squaring, flowering and boll-setting stages respectively compared to non-stressed controls, highlighting cotton's compensatory growth ability (25). These adaptive responses reflect the resilience of cotton when exposed to waterlogging stress and its potential

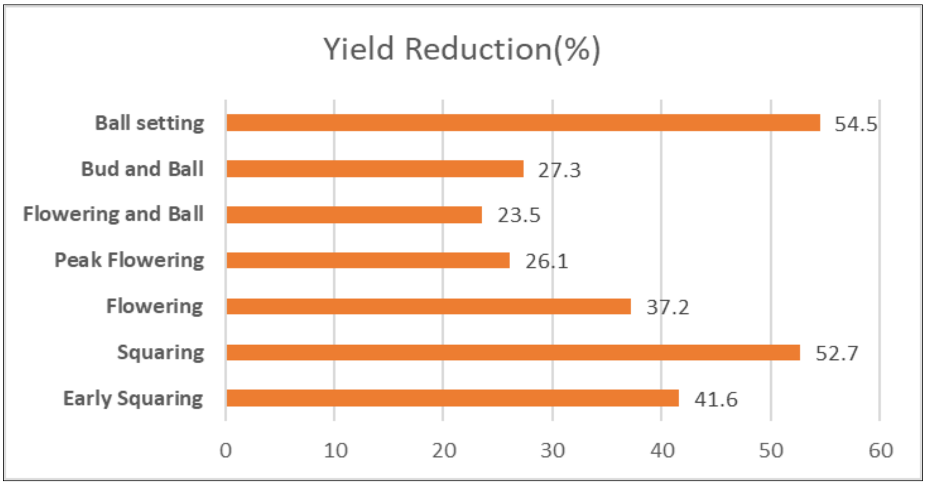

Fig. 3. Yield reduction in cotton across different growth stages under waterlogging conditions.

capacity for recovery.

Drought

Drought stress inhibits most physiological processes such as photosynthesis, water regulation and cell growth in plants, hence causing stunted growth and reduced crop yields. According to previous study (26), on average, one drought episode lowers agricultural GDP by 0.8 % at the global scale.

Plants respond to drought through various morpho-anatomical, physiological and biochemical changes that help them tolerate stress. These adaptations often include mechanisms for water conservation, such as reduced transpiration and enhanced water use efficiency (27). Drought stress has induced significant effects on the growth, yield and fibre qualities of cotton (28). The vegetative and reproductive stages of the plant are affected such that during reproduction, it suffers from lower internodal spacing and shorter branches, thereby producing fewer fruiting bolls (29). Drought stress causes enormous structural, physiological and molecular losses and ultimately reduces lint yield (30).

Response of cotton to drought stress

Cotton has multiple adaptive strategies to counter avoidance, escape, tolerance and recovery phases (31). Drought avoidance can be simply stomatal regulation that is augmented by an effective root system. Some of these mechanisms involve stomatal regulation, root growth and osmotic adjustment (32). Crops also experience the early stomatal closure and shedding of leaves for hydraulic balance under severe drought (33). In addition, cotton produces large, deep root systems that are resistant to drought (34). Osmo protectants such as proline, glycine betaine and salicylic acid have been shown to increase the drought tolerance of plants (35). A major consequence of drought is osmotic stress in cotton (31). ABA signalling pathways play crucial roles in both drought and salt stress. For example, the MAPK cascade (GhMAP3K62-GhMKK16) triggers increased ABA contents, which are responsible for drought tolerance through stomatal regulation (36).

Heat

High temperatures in arid and semiarid areas reduce the growth, development and productivity of crops (37). Morphological changes including leaf scorching and senescence occur together with disruptions in photosynthesis, respiration and water relations caused by heat stress (38). It also impacts soluble sugar and protein levels and has an oscillating effect on osmotic pressure. In general, the exposure to heat and drought stresses tends to have more destructive effects than exposure to either stress alone (39).

High temperatures during the reproductive stage of cotton are damaging. A higher temperature than optimal 38 °C reduce the germination rate of cotton seeds and when the soil temperature is high, roots develop poorly and hence produce a weak crop stand (40). Temperature above 40 °C reduces boll maturation and thus results in the production of smaller, lighter bolls (41). For example, in Nanjing, China, a temperature increase of 2-3 °C above the optimal temperature led to a decrease in biomass of 10 % and a loss of 40 % in yield. A previous study revealed that, heat stress increased the micronaire value of cotton fibres, resulting in coarser fibres with reduced strength (42).

Mechanisms of heat tolerance in cotton

High temperature increases metabolic imbalances within cotton, resulting in the accumulation of excessive ROS. The concentration of ROS and the capacity of antioxidants have widely been used to characterise heat tolerant varieties of cotton (43). H_2O_2 applications to the leaves of cotton plants also promote heat tolerance without causing yield reductions afterward. In a previous study, a 30 ppm H_2O_2 spray applied during critical growth stages square initiation, flowering and boll formation-effectively minimized heat-induced yield losses (44). Heat shock proteins (HSPs) are also crucial for maintaining homeostasis during heat stress. Over expression of HSPs and general stress response genes in high temperature tolerant cotton genotypes helps them withstand extreme temperatures. The main heat mechanisms are depicted in the Fig. 4.

Agronomic interventions to mitigate abiotic stress

Biostimulants

Biostimulants have emerged as promising tools to increase crop resilience against abiotic stresses, which significantly impact plant growth and yield (45). They enhance nutrient uptake and utilisation, efficiency, while also improving tolerance to drought, salinity and other extreme temperatures (45). One of the key benefits is low toxicity or non-toxicity; there is no long-term accumulation into the environment that would be considered harmful (46). Biostimulants exist in various forms and can be broadly categorized into six main groups on basis of the source of raw

Table 1. Categories and sources of biostimulants

Categories	Method of application	Source	References
Seaweeds and plant extracts	Foliar treatments	Brown, red and green algae	(48)
Humic substances	Foliar or soil amendments	These substances are generated from the decomposition of plants, animals and microorganisms are further transformed by the metabolic processes of soil microbes	(49, 50)
Micro organisms	Seed treatment	Fungi, bacteria and PGPR, yeasts	(51)
Nanoparticles	Foliar treatments or in nutrient solution	Nano ZnO	(52)
Hydrolysed proteins and amino acids containing products	Products are obtained from through enzymatic or chemical hydrolysis of proteins into peptides and free amino acids	Thermal, enzymatic and chemical hydrolysis of proteins (or by combining these, hydrolysis types) from both plant and animal sources	(53)

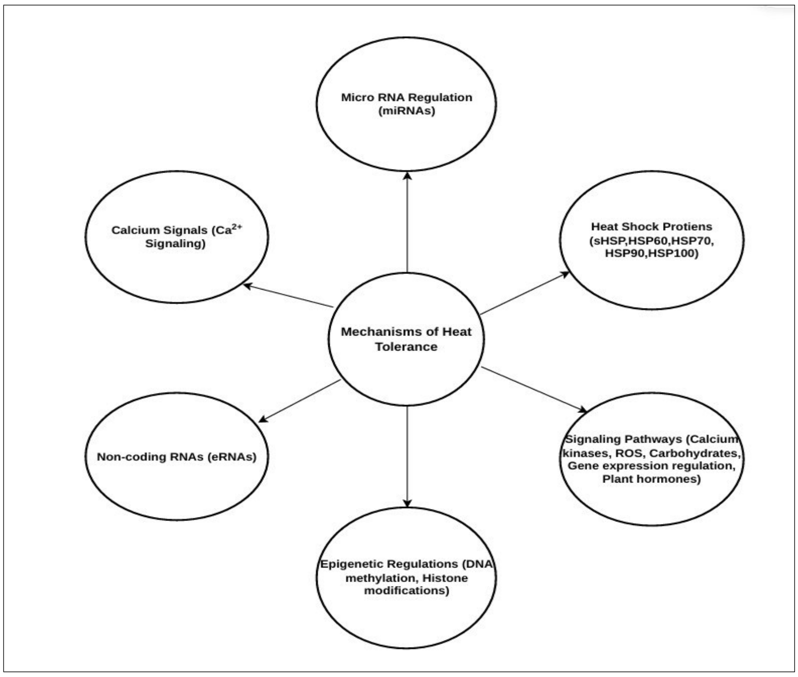

Fig. 4. Adaptive mechanisms of heat tolerance in cotton.

material: seaweed extracts, plant extracts, protein hydrolysates, humic substances, inorganic compounds and microorganism (47) as shown in Table 1.

Plastic mulching

Plastic mulching provides several short-term advantages in agriculture, such as boosting crop yield, enhancing fruit quality and conserving soil moisture. Its ability to retain moisture helps alleviate drought stress, thereby supporting better growth and productivity in crops like maize and bell pepper (54). Plastic mulching enhances photosynthetic efficiency and grain filling and increases overall crop productivity in water stressed crops. It also controls soil temperature, ensuring quicker flowering time in maize, with reduced cold stress (54).

In cotton, plastic mulching alleviates heat stress related to high canopy temperatures and improves the water potential of the leaves (55). It can also reduce the adverse effects of soil salinity to cotton yields (56). Plastic mulching when applied early, promotes better stand establishment, plant growth and lint yield in saline fields (57). Plastic mulching increases the retention of soil moisture and soil temperature which advances early cotton growth and increases canopy photosynthetically active radiation (58). It is very promising in saline regions for increasing crop stand establishment and profitability (59).

Seed priming

Seed priming involves pre-sowing treatment of seeds with specific agents to induce stress tolerance mechanism (60). This method has been found to be most effective in the development of resistance in cotton against harmful environmental conditions. Priming with phytohormones is especially effective in minimizing the adverse impacts of abiotic stresses (60). Seed priming can also induce epigenetic modification and trans generative memory, which leads to increased resistance against stresses transmitted to subsequent generations (61).

Chemical priming using both natural and synthetic compounds is an effective strategy to enhance plant tolerance to abiotic stresses. This, in turn, contributes to improved crop yield (62). Other types of seed priming such as osmotic solution based, water based and plant growth regulator (PGR) based and chemical used, can enhance

Table 2. Various types and methods of seed priming

Techniques	Method	References
Hydropriming	Soaking seeds in plain water and dehydrating them to their original moisture content before sowing	(63)
Osmopriming	Hydrating seeds in a low-osmotic aerated solution with varying time durations and water potentials	(64)
Chemical priming	Priming agents such as $ZnSO_4$, $CuSO_4$, KH_2PO_4, chitosan, choline, putrescine, paclobutrazol and selenium are used	(65)
Biological priming	Incorporating seed imbibition with biologically active bacterial inoculants in the priming solution	(66)
Hormonal priming	Soaking seeds in a solution containing PGRs like gibberellic acid (GA3), salicylic acid, or abscisic acid to enhance seed germination and stress tolerance	(67)
Solid matrix priming	Seeds are moistened and combined with an organic carrier, adjusting the moisture content to a level below the threshold needed for germination	(68)
Nutri priming	Soaking seeds in a nutrient solution, such as micronutrients or macronutrients (e.g., Zn, K, or P), to improve seedling vigor and early plant growth	(69)

drought tolerance. These factors help plants survive adverse environmental conditions, which results in a relatively higher crop yield. Other important techniques for seed priming are listed in the Table 2.

Nanoparticles

Nanoparticles (NPs) are considered emerging tools of alleviating of abiotic stress and increasing crop productivity (70). These tiny particles can penetrate plant tissues through the aerial organs of plants, such as stomata, cuticle, epidermis, hydathodes, or other openings (71). The physiological and morphological impacts of NPs vary among different species, development periods, development agents, application methods and doses and durations time of exposure (72). The application of NPs plays a key role in reducing the adverse effects of salinity stress faced by plants. It promotes plant growth along with a reduction in reactive oxygen species generation because of the regulation of plant nutrient homeostasis and chlorophyll florescence activity (73). Various methods such as seed incubation, foliar spraying and irrigation can be used for NP application (70). Foliar application of NPs in cotton during drought, increases the total phenolic content, total soluble protein content, total free amino acid content, proline content, total antioxidant capacity and CAT, POD and SOD activities (74). Under drought stress, the application of SiO_2 NPs can increase the shoot length and RWC in barley, while reducing the formation of superoxide radicals and membrane damage (75).

SiO_2 NPs significantly increase the germination, growth and productivity of plants under stress. This may be due to their uptake through the roots through formation of a thin layer in the cell wall that enables the plant to tolerate different stresses (76). Although silver NPs toxic at relatively high concentrations, when they are reduced to nano size (25 -50 nm), Ag NPs have shown unique properties, increasing plant vigour, productivity and the photosynthetic rate (77). Studies on titanium dioxide (TiO_2) nanoparticles have shown that nano TiO_2 and nano SiO_2 significantly enhance pigment content, antioxidant activity and yield in cotton under drought stress. Optimal concentrations of nano TiO_2 (50 ppm) and nano SiO_2 (3200 ppm) have been found to reduce the negative effects of drought. They do so by boosting chlorophyll levels, enhancing antioxidant enzyme activities (CAT, SOD, POX, GR) and protecting chloroplast function. Additionally, they support osmotic regulation by increasing proline and sugar accumulation.

Nutrient management

Macronutrients such as N, P, K, Ca etc. and micronutrients such as B, Zn, Fe, Cu, Si, etc., availability are important for crop growth as well as crop resilience against climate induced stress conditions in the form of drought, heat, heavy metals, salinity and submergence. Nutrient deficiencies at the time of crop production strongly affect a plant growth as well as tolerance ability to abiotic stresses.

Among macronutrients, nitrogen has a unique interaction with drought stress. Nitrogen is crucial for plant metabolism and can influence varietal response under stress. This strategy is relatively more effective in arid areas than in temperate zones (78). Nitrogen application enhances crop growth and yield under mild salinization conditions without significant effects of severe salinity (79). Furthermore, N increases the activation of the antioxidant defence system in cotton under abiotic stress conditions (80). The next macronutrient is P, which also plays an important role in cotton, especially under stress conditions. Foliar spraying of phosphorus at the boll formation stage enhances the quality of the fibre, but the boll weight and yield of the cotton seeds also increased (81). Potassium increases the turgor pressure and osmotic pressure of stomatal cells when applied under water deficiency conditions thereby ensuring the water supply and imposing drought tolerance as well as water relations. In addition, potassium application at the optimal fertilizer amount also mitigates the adverse effects of soil salinity on the agronomic and physiological parameters of cotton crops (82). In addition to being a macronutrient, silicon is also considered an essential nutrient that can alleviate abiotic stress including waterlogging, heat, drought and cold.

Application of the nitrate

Recent research highlights the crucial role of nitrate in mitigating abiotic stress in plants. Increasing nitrate availability can alleviate salt stress effects in wheat seedlings by increasing nitrate reductase activity and improving growth parameters (83). Nitrate transporters, which are primarily responsible for nitrate absorption and translocation, are extensively involved in coping with adverse environmental conditions (84). The intricate relationship between nitrate/ammonium and abiotic stress responses involves core signalling regulators, which can be leveraged to improve crop growth and productivity (85). Nitrate functions not only act as an essential nutrient but also as a key signalling molecule that regulates plant growth and stress tolerance. This regulation is mediated through pathways involving Nin like proteins (*NLP*s) and calcium dependent protein kinases (*CPK*s), which coordinate nitrate sensing and gene expression responses to optimize growth and resilience under stress. Understanding the integration of nitrate signal transduction and abiotic stress responses is vital for developing crops with increased nitrogen use efficiency and resilience (86).

In cotton crops, nitrate application plays a significant role in mitigating the negative effects of waterlogging. Cotton plants, which are sensitive to waterlogged conditions, suffer from a restricted root oxygen supply, leading to poor nutrient uptake, especially that of nitrogen. However, nitrate supports the formation of adventitious roots in cotton, which improves the ability of plants to tolerate waterlogged conditions by allowing better oxygen exchange and nutrient uptake (87). Under waterlogged conditions, nitrate remains a more easily accessible form of nitrogen for cotton than ammonium does. This improves nutrient availability and helps sustain cotton growth (87). Waterlogged soils trigger the production of ethylene, a stress hormone that inhibits root growth and accelerates plant senescence. Nitrate has been found to reduce ethylene accumulation, thereby maintaining cotton root health and plant growth (24).

Table 3. Other agronomic measures and their efficacy against various abiotic stresses in cotton

Agronomic measures	Stress type	Features	References
Foliar application of osmolytes, potassium and growth regulators	Drought	Improve osmotic adjustment, water use efficiency and regulates stomatal conductance	(88)
Application of $FeSO_4$	Waterlogging	Ameliorated the negative effects of iron chlorosis, returning cotton foliage to its normal colour	(89)
Anti-transpirants	Drought	Decreased water loss through transpiration and a reduction in photosynthesis, resulting in lower water consumption	(90)
Early sowing	Heat stress	Escape water and heat stress during sensitive growth periods	(91)
Irrigation management	Salinity stress	Maintaining soil water content near field capacity through frequent, low-volume irrigation is recommended	(92)
Conservation tillage	Moisture stress	No-till and minimum tillage, can enhance soil water availability and improve crop physiological functions under moisture stress condition	(93)
Application of sodium nitroprusside (SNP)	Waterlogging	Foliar spraying of SNP in waterlogged cotton decreased the malondialdehyde content and the activities of alcohol dehydrogenase and pyruvate decarboxylase in waterlogged cotton at 10-d post stress relief by 15.2 %, 42.4 %and 38.2%. Additionally, it increased the contents of auxin (IAA), gibberellic acid (GA)and chlorophyll and the photosynthetic rate by 28.6 %, 59.6 %, 12.1 %and 6.4 %, respectively, while decreasing the levels by abscisic acid (ABA) and ethylene contents by 12.5 % and 8.5 %, respectively, compared to no SNP spraying.	(94)
Shading and windbreaks	Lodging and drought	Windbreaks can decrease evapotranspiration by up to 50 % during summer, while shading can reduce solar radiation to 9 % of full sunlight near dense windbreaks	(95)
Crop rotation and intercropping	Moisture stress	Intercropping produces 38 % more gross energy and 33 % more gross income while using 23 % less land compared to monocultures, with benefits observed in both stressful and non-stressful moisture conditions	(96)
Silicon management	Salinity stress	Reduces salt uptake, stimulating antioxidant defense systems and promoting photosynthetic activity in stressed plants	(97)
5-Aminolevulinic acid	Salinity stress	Enhanced seedling germination	(98)
Furrow seeding	Salinity	Reduces root-zone salinity, increases soil temperature and enhances stand establishment and lint yield compared to flat-seeded cotton without mulching	(59)
Biochar application	Heavy metal stress	Biochar, with its greater cation exchange capacity emits Ca and Mg on its surface, which contributes to decrease the concentration of heavy metals in the soil	(99)
Use of superabsorbent	Heavy metal stress	A reduction in the bioavailability of heavy metal by SAP can be attributed to the presence of high-density metal-chelating groups in the gel, which can effectively bind to the heavy metal and hence reduce the numbers of heavy metals in the soil environment	(100)

In addition to these interventions, other agronomic measures with proven efficacy against various abiotic stresses in cotton are presented in Table 3.

Conclusion

The cultivation of cotton, a cornerstone of the global textile industry, is increasingly threatened by various abiotic stresses, including drought, salinity, extreme temperatures and waterlogging. Addressing these challenges is critical to sustaining cotton production and ensuring fibre quality. This review comprehensively examines the agronomic practices that can be implemented to increase abiotic stress tolerance in cotton. Soil and crop management practices such as plastic mulch application have shown substantial benefits in enhancing soil structure, moisture retention and nutrient availability. Nutrient management plays a crucial role in stress mitigation. Tailored applications of macro- and micronutrients, particularly potassium and silicon, have been identified as effective in improving cotton resilience to salinity and drought. These nutrients aid in modulating physiological and biochemical pathways, enhancing the ability of plant to withstand adverse conditions. The use of biostimulants, such as seaweed extracts and beneficial microbes, is also gaining attention because of their ability to increase nutrient uptake and enhance abiotic stress tolerance. Advanced planting techniques, including optimized planting dates and spacing, can further increase stress tolerance by reducing competition for resources and optimizing plant density. The development of stress-tolerant cotton cultivars through traditional breeding and modern biotechnological approaches holds immense promises. When combined with tailored agronomic practices, these genetically enhanced cultivars can significantly bolster the resilience of cotton to abiotic stresses. By adopting such integrated practices, farmers can sustain cotton productivity and quality despite escalating environmental challenges. Continuous research and extension services are necessary to refine these practices and ensure their widespread adoption. Ultimately, a collaborative effort involving researchers, farmers and policymakers are needed to effectively combat abiotic stresses and secure the future of cotton agriculture.

Authors' contributions

AMJ wrote the manuscript draft and NV revised it. SS and DJ verified contents. PD helped to align the content. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare**.**

Ethical issues: None

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