published by

EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 74 (2026): 16 - 42
Journal homepage: https://eqa.unibo.it/

Integrated agronomic strategies for alleviating salinity stress and enhancing cotton yield

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Article info
Received 19/3/2026; received in revised form 28/5/2026; accepted 15/6/2026
DOI: 10.60923/issn.2281-4485/24485

Abstract

Salinity is one of the most threatening stress for cotton. Cotton is considered a moderately salt-tolerant crop with a salt tolerance limit of 7.7 dS m^{-1}. Stress is always deleterious for cotton growth, yield, and quality of cotton. The degree of sensitivity to salt stress varies in a dependent position with growth stage and type of salt. Cotton reacts to salinity, and its ability to cope with it and the management methods might prove useful in helping to find ways to enhance the production of cotton under saline environments. Several of the studies have demonstrated that the germination, seedling phases and emergence are much more sensitive to salinity stress in a comparative perspective from other later phases. Flowering occurs later, and fewer fruiting sites, fruit drop, and smaller boll size ultimately influence seed cotton yield; its partitioning is the major aspect of cotton modulation under salt stress. This study shows that high level of salts in the soil affect the metabolic activities of the cotton plants mostly through osmotic stress, nutritional imbalance and toxicity from the salts' ions; sodium and chloride. The metabolic disorders may suddenly bring down cotton growth and lint yield, most especially in moderate to highly saline soil. In this review, we study different of agronomic practices such as mulching and furrow seeding, plant density management, increasing soil moisture and temp, water management, utilization of root associated microorganism, drip irrigation, crop rotation, biochar, seed priming, flat-sowing technique, ridge planting technique mitigating soil salinity, reducing salinity effects on cotton and improving plant growth of the cotton plant. Cotton genetic studies on salt tolerance indicated that most biochemical, physiological, agronomic, and fiber traits are genetically regulated and have significant QTL effects. But with biochemical and molecular biology tools available now, it has become possible to look at the intricacies of salt tolerance at the transcript level. This review highlighted integrated agronomic strategies for alleviating salinity stress and enhancing cotton yield.

Keywords*: Agronomic practices, cotton, functional genomics, growth stages, drought stress, physiological, soil salinity, salinity tolerance.*

Introduction

The soil salinity is a primary factor that negatively affects crop productivity in areas constituting about 17% of the world's cultivated land and about 45% of the irrigated lands(Lobell *et al.,* 2007;Shrivastava *et al.,* 2015;Awan *et al.,* 2024). However, it has been categorized as one of the crops that are more salt tolerant among the common significant crops and allowed for the reclamation of salty soils; growth, germination, and maturation of the cotton crop are negatively impacted by high levels of salinity in the soil (Higbie *et al.,* 2010). The most common way of presenting the degree of soil salinity is by EC of a (ECe), and soils with ECe greater than 4 dS/m at 25°C are considered saline. Low salinity levels are defined as ECes of 8–12, 4 – 8, and ≥ 12 – 16 dS/m (El-Swaify, 2000). High salinity prevented germination and emergence and reduce seed cotton yield, cotton shoot growth and, most probably, the fibre quality of the cotton seed (Khorsandi *et al.,* 2009). However, the responses of plants to salinity depend on the degree of salinity, and the yield of cotton was reduced by 50%,25%, and 10% by ECes of 16, 12, and 10 dS/m, respectively. As part of research conducted over the

DOI: 10.60923/issn.2281-4485/24485

last thirty years, several ways and practices that can help relieve the detrimental impacts of salinity have been identified. All the aspects of the relationship between soil salinity and the *cotton* plant have been somewhat developed (Gorham, 2009; Maryum *et al.,* 2022). Cotton is one of the most indispensable natural fiber crops for edible oil and biofuel. This cotton plant has to go through several abiotic and biotic stresses in its life cycle, with salinity emerging as one of the most critical challenges threatening sustainable cotton production globally. However, cotton is a moderately salt-tolerant crop with a threshold salinity level of 7.7 dS m^{-1}. This study has demonstrated that salt stress disrupts ionic balance, and the osmotic stress at the cell level affects energy at the cell level and photo-synthesis, causing redox distortion. Therefore, limited photosynthesis affects the cellular metabolic process that, in return, causes disorderly plant development (Zhang *et al.* 2016; Zhang *et al.,* 2013; Awan *et al.,* .2024). Estimates that 45 million ha of the world's irrigated area is salt-affected, resulting in an annual loss of $27.3 billion. It is estimated that 20% of the cultivated land globally and 33% of the irrigated agricultural area of the world is salt-affected, and the extent of the affected area is expanding at 10% per year. Global statistics indicate that by 2050, well over 50% of the arable land will be affected by salt. Sources of salinity and water. Logging includes poor irrigation management, poor quality water irrigation, and unavailability of proper drainage systems in Pakistan and India, respectively ((Hossain *et al.,* 2010; Jamil *et al.,* 2011;An.m *et al.,* 2025). Grown all over the world for its significant production of seed oil, natural fibers cotton is a major agro-industrial crop. Among the top cotton-growing countries are China, the USA, India, Brazil, Australia and Pak. Despite ranking among the top 5 countries in the world, Pakistan's yield is lower than that of the other leading countries because of a number of abiotic and biotic variables, with heat, drought and salt (Chaudhry *et al.,* 2022). The production of cotton is particularly threatened by salt, one of several abiotic stresses. Cotton is being shifted to alkaline soils and saline soils in Pakistan as a result of competition from cereals and other cash crops. In addition to these considerations, the growing need for natural fiber in textiles for societal and population-related reasons makes it essential to manufacture large quantities of high-quality cotton fibers. (Zafar.*et al.,* 2024).

Database of cotton production and literature

According to the most recent estimate from 2020, the world's cotton production is 24.2 × 106 t, more than twice as much as it was in the 1960s. Furthermore, China leads the globe in production with 6 million tonnes, followed by the US and India (Figure 1a,b) (Vitale *et al.,* 2024).

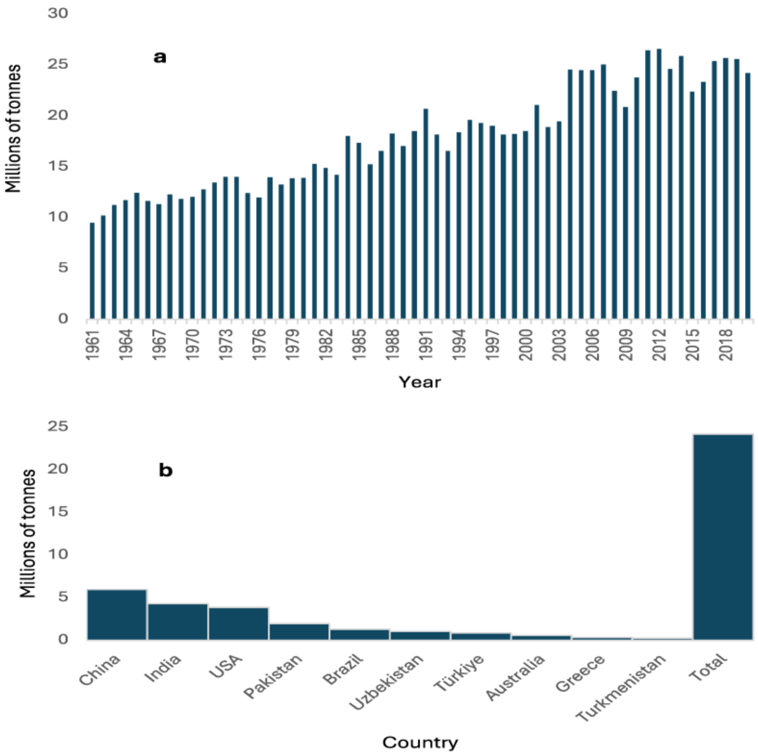

Figure 1
*World cotton production: (**a**) production of ginned cotton lint around the world (1961–2021); (**b**) top 10 producers of cotton lint (Vitale et al., 2024).*

DOI: 10.60923/issn.2281-4485/24485

Similar to this, there has been a significant increase in scientific study on sustainable cotton production in recent decades. When searching for "sustainable cotton" in the Scopus® database, there are 111,000 document results, with the first article published in 1981 and 22,800 in 2022.

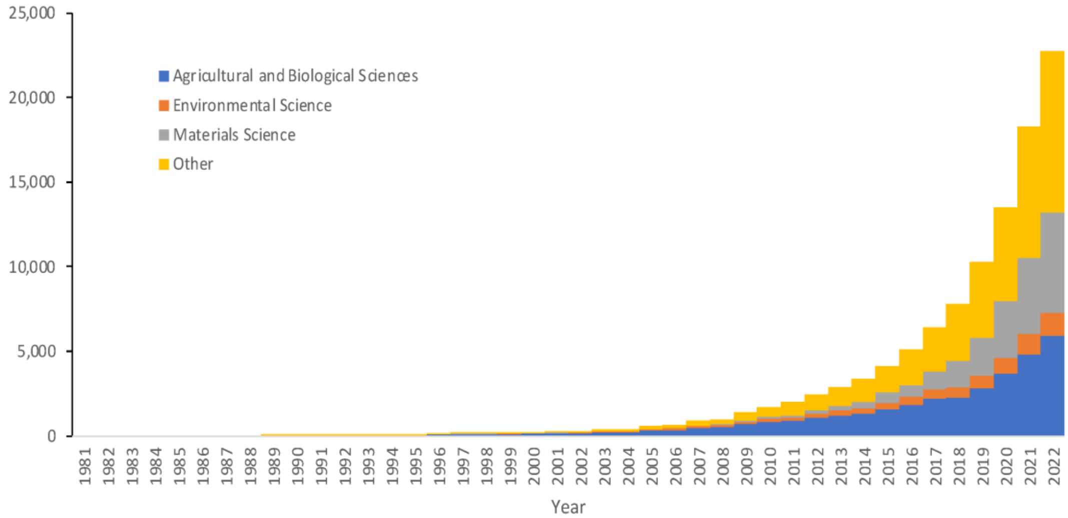

Figure 2
International scientific articles on "sustainable cotton," Scopus®, 1981–2023 (Vitale et al., 2024)

Global status of salt stress

Over half of the world's countries face problems with salinity, which is a significant issue with varied degrees of impact on affected areas. According to Saddiqe *et al.* (2016), it usually happens in semi-arid and arid parts of the world, especially in low-lying soils where free salts are deposited. Australia and Asia are the most salt-affected regions of the world regarding soil classification. The Pacific, Australia, and Asia salinity issues affect about 6% of the area. Pakistan is mainly concerned by salinity because it is in an arid to semi-arid environment. According to reports, 6.28 million hectares of Pakistan's 22 (Mhs) of agricultural land are impacted by salt (Alam, 2000). Saline sodic soil makes up around 60.5% of Pakistan's salt-affected soil, with the re-maining 39.5% experiencing salinity. Salt stress results in the loss of 40,000 hectares annually, costing the US economy $3 billion annually (Ashraf *et al.,* 2000b). This issue is particularly prevalent in dry regions with lower rainfall and higher evapotranspiration rates. Abiotic stresses that significantly reduce crop production po-tential are moisture scarcity. Low soil moisture levels decrease plant intercellular activity and lower plant yield potential. As a result, drought stress is considered the primary abiotic stressor that reduces plant quality and production (Schittenhelm *et al.,* 2010; EL Sabagh *et al.,* 2020b; Raza *et al.,* 2020). One essential crop that is susceptible to water scarcity is cotton. Moisture defi-ciency is commonly used throughout the boll forma-tion stage in several cotton-growing regions. Compared to previous stages, Gossypium is more vulnerable to drought stress during the boll development phase. The weather prediction determines how long and severe the moisture stress is (Loka *et al.,* 2012; Giorgi and Lionello *et al.,* 2008; Loka *et al.,* 2012). Numerous researchers have examined the detrimental effects of moisture stress on cotton production and fiber quality, with reproductive development particularly vulnerable to salinity. Using different degrees of field capacity, water stress can reduce boll production and boll weight. Moisture deficit is linked to increased and decreased yield-related traits (Rahman *et al.,* 2018; Lokhande and Reddy *et al.,* 2014). Lint yield is the primary plant characteristic that is decreased under moisture defi-ciency stress, which typically varies according to the state of characteristic fruit branches. Additionally, moi-sture deficiency stress changes the distribution of boll biomass and the number of seeds per boll on upper fruiting branches. Fiber length and quality decrease as water supply decreases in better fruiting branches. Bet-ter fruiting branches have higher micronaire efficiency under the same moisture conditions, and dryness has no long-term effects on micronaire efficiency (Rahman, 2019).

Negative impacts of salinity on cotton

Around 20% of irrigated land worldwide is affected by soil salinity, which severely hinders the production of cot-ton, a vital cash crop (Ashraf, 2002; Li, 2025). Cotton production and fiber quality are decreased by salinity stress, which also causes oxidative stress, increases ionic toxicity, and interferes with the uptake of nutrients and water (Munns and Tester, 2008). In saline a-

DOI: 10.60923/issn.2281-4485/24485

reas agronomic techniques are essential for reducing nega-tive impacts and increasing productivity. Cotton suffers from reduced plant growth, seed cotton, boll number and per plant production in saline conditions. Effective management of cotton requires knowledge of the detrimental effects of soil salinity. Field-grown cotton exhibits effects of salinity at several phases of growth, including seedling, germination and vegetative, and maturity. Cotton seed germination is frequently delayed and inhibited by high soil saline levels, as well as aberrant plant growth that shows as stunted development of roots and shoots. Cotton's biological or economic yield is adversely affected by salinity stress, which is caused by a number of biochemical processes and physiological changes at the molecular levels and cellular (Meloni.2003; Nawaz.2010; Greenway.1980). It is well accepted that there are three main ways in which soil salinity stress negatively impacts cotton crops and plant growth. First, osmotic water stress is brought on by an excessive concentration of salt. Second, some ion toxicity is brought on by elevated sodium chloride ion concentrations. Finally, an imbalance in the nutritional ion balance caused by an overabundance of sodium chloride ions reduces the absorption of essential ions such as potassium, NO^{3-} , PO_4^{3-} , and others. Salt stress affects the various stages of cotton growth, which is essential for managing saline soils. The cotton growth stages are shown in Figures 3 and 5.

Germination. According to Ahmad *et al.* (2002), salt stress during the young seedling phases, growth, and germination than during other stages. After 10 dS m^{-1}, the germination rate was reduced in cotton. Cotton likewise exhibits delayed germination and formation stages in response to saline stress (Ma *et al.,* 2011). Compared to typical plants, the growth of plants was delayed by up to 4–5 days at salinity stress levels of 15–20 dS m^{-1}. Inadequate germination causes the plant population to decline, which in turn causes a rapid decrease in cotton yield (Saqib, 2002). At the germination stage, salt tolerance could be assessed using the vigor index, fresh mass, germination potential, and germination rate (Guo, 2011).

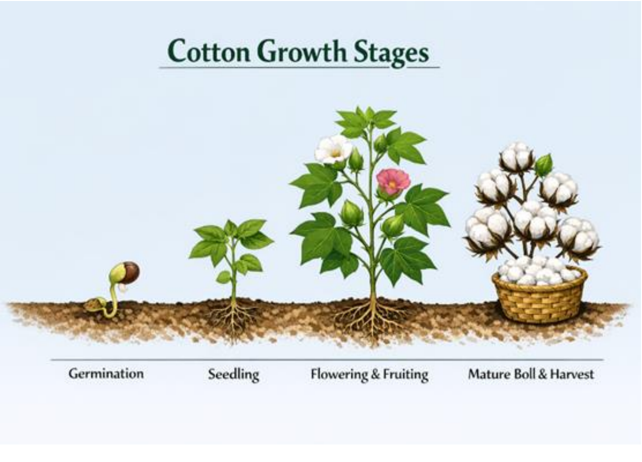

Figure 3. *Cotton plant growth stages*

Root growth. Because salinity inhibits root length and decreases the quantity of secondary roots, it typically slows down root growth. Higher concentrations reduced the length of primary roots, although modest salt stress also slowed the length of secondary roots, according to Leidi *et al.,* (1994). The roots' ionic influx and transfer toward the shoot are essential for plant growth. A lesser amount of Na^+ ion retention in the roots may be the reason for a comparatively lower inhibition of root growth than in the shoot. Many soils saw a significant decrease in root growth as salinity increased. However, clay, loam, and intermediate soils exhibited the most significant suppression in root development, fresh weight, and dry weight, whereas sandy soil showed the least effects (Shelden *et al.,* 2023;zou *et al.,* 2021).

Shoot growth. Cotton is categorized as a crop that can withstand some salt, although more significant salt concentrations harm vegetative growth. Shoot growth is more sensitive to salinity than roots; salt stress lowers the shoot/root ratio. Nonetheless, other researchers found that shoot growth was enhanced by moderate salt stress (Gul.2025.Dong.2024). The presence of micro-nutrients in the form of contaminants in the saline moderate for growth or the nutrition-sparing effect could be the cause. Research conducted under salt stress at the seedling, flowering, pre-flowering, six-leaf, and boll development phases revealed that the 6-leaf stage was the most vulnerable (Zhao *et al.,* 2020;Dong *et al.,* 2020;Kent and Maryam *et al.,* 2022;Anwar *et al.,* 2023).

Boll development and yield. The two main factors influencing yield are boll size and number. Cotton yield decreased when the salt level increased because there were fewer bolls, and their weight reduced. Reduced fruit-bearing position, delayed flowering, and comparatively higher flower and boll shedding under salt stress are the causes of a decrease in mature bolls. The detrimental effects of salt stress on vegetative growth, which ultimately delayed the initiation of flowering, could be the cause of the delayed flowering. Cotton production is significantly influenced by the 60–87% synthetic sucrose transferred from the LSCB to growing bolls. Although sucrose accumulation in

DOI: 10.60923/issn.2281-4485/24485

LSCB is un-affected by saline environments, its effective transport to developing bolls is slowed, which lowers the weight of the bolls (Peng *et al.,* 2016a). At 17.0 dS m^{-1}, Gossypium *spp* production decreased by 50%; however, moderate salt had no adverse effects on growth, whereas higher salinity caused premature leaf senescence and shedding (Gao *et al.,* 2024;Anwar *et al.,* 2023;Peng *et al.,* 2016). 90% less yield was produced when cotton plants were irrigated with highly saline water while budding.

Fiber quality. Although fiber quality is inherited, environmental factors can have an impact. While fiber fineness showed an upward tendency, salinity stress decreased, strength, maturity and fiber length. Micro-naire values, strength, and fiber length drastically reduced as the quantity of sodium ions increased. Because it influences the processes of photosynthesis, cellulose deposition, and sugar transport, increased EC probably affects fiber maturity. Reduced cellulose deposition leads to less mature fiber and an inevitable decrease in cross-sectional area. Cellulose deposition is the primary determinant of fiber quality, and sucrose metabolism is essential to cellulose production. Cellulose makes up about 85% of mature fibers; it is syn-thesized and accumulates during fiber thickening, and its deposition starts following fiber elongation due to increased cellulose synthesis. Fiber quality deteriorated due to salt-sensitive types', the sucrose transformation rate and cellulose contents rapidly lessened as saline levels rose. Because sucrose phosphate synthase, alkaline invertase, and the metabolic enzymes acidic invertase are inhibited, sucrose is accessible in saline conditions. (Longenecker *et al.,* 1974; Yfoulis and Fasoulas *et al.,* 1973; Fernandes *et al.,* 2004).The boll development and fibre quality is shown in figure.4.

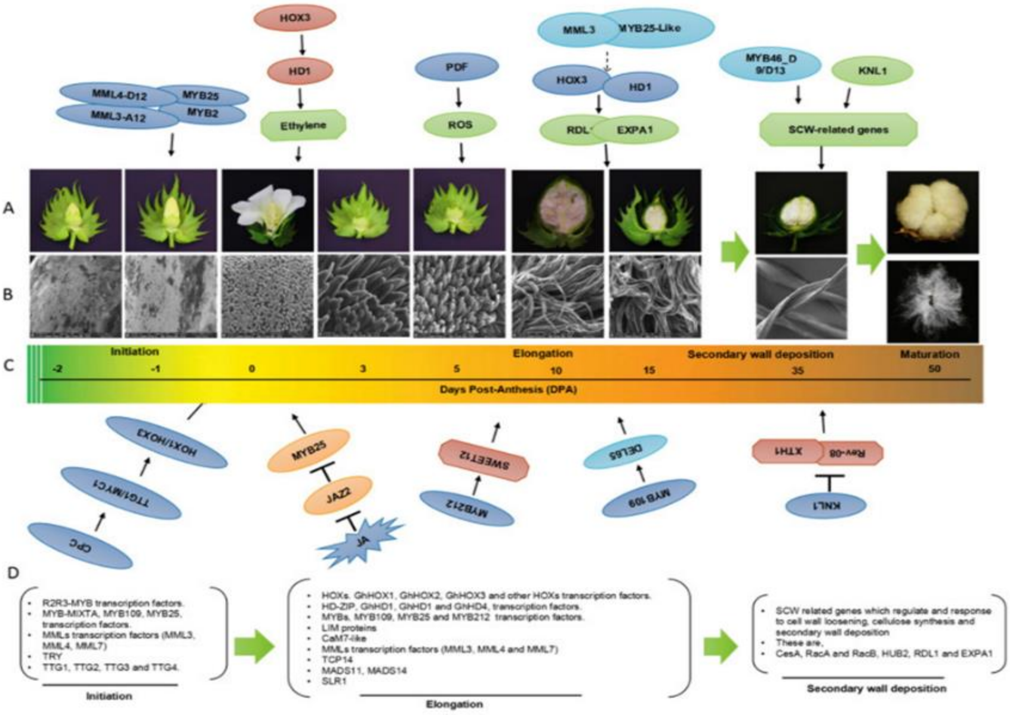

Figure. 4
Role of TFs in different stages of cotton fiber development.
*(**A,B**) Boll and fiber development.*
*(**C**) Fiber developmental stages include initiation, elongation, secondary wall biosynthesis, and maturation.*
*(**B**) Scanning electron microscope (SEM) images from -2 DPA (ovule fiber initiation) to 35 DPA (fiber development completion). SEM scale = 100 µm.*
*(**D**) Key TFs are involved in the regulation of cotton fiber development (Jan et al., 2022).*

Yield and yield-related components. The most critical consequence of Gossypium production, lint production, has been the subject of many field experiments investigating the effects of salt or drought. There have been reports of unfavorable relationships between yield and physiological and/or morphological characteristics. A decrease in cotton output has been noted as salt levels rise due to fewer bolls and lower boll weight. Numerous factors, including low fruit-bearing areas, delayed flowering, boll shedding under salt conditions, and a relative increase in flowers, contribute to the decrease in mature bolls (Anagholi., 2005). Cotton production is significantly impacted by the translocation of up to 60–87% of the produced sucrose from the (LSCB) to growing bolls. Under salt stress, sucrose's effective translocation towards developing bolls is delayed, resulting in decreased boll weight even while its accumulation in LSCB stays constant. While a moderate salinity level did not negatively impact growth, a nearly 50% decrease in cotton production was noted at 17.0 dS m^{-1} of salt concentration. Premature leaf withering and shedding occurred when

DOI: 10.60923/issn.2281-4485/24485

the saline level increased. A few further studies (Ashraf and Ahmad, 2000; Peng, 2016) additionally noted that increasing the salinity from 7.7 dSm^{-1} to 17.0 dSm-1 resulted in an almost 50% decrease in yield.

Seed oil content. Typically, cottonseed has between 20 and 23 percent oil. According to a different study, dried cottonseed contains 28–44% oil, including saturated and unsaturated fatty acids. It is typically assumed that higher levels of salt stress cause the amount of seed oil to decrease. Six genetically distinct cotton lines with varying degrees of salt tolerance showed that when the growing medium's salt concentration rose, the oil content decreased. Another study found that cottonseed from plants exposed to salt stress had lower oleic and linoleic acid levels. However, compared to genotypes susceptible to salt, those more salt tolerant produced a more significant percentage of seed oil content. Due to the wide range of plant traits specific to each species, cotton's tolerance to salt varies within and between species. Because most of this variety is genetically additive and natural, such genomic diversity would be extremely useful in boosting cotton's ability to withstand salinity through breeding and selection (Dowd *et al.,* 2010; Shang *et al.,* 2016; Khan and Gregori. 2002; Ahmad *et al.,* 2007). The purpose of this review article is to critically analyze and synthesize current knowledge on the biochemical, molecular mechanisms and physiological underlying salinety tolerance in cotton(*Gossypium spp.*). This review highlighted integrated agronomic strategies for alleviating salinity stress and enhancing cotton yield. By integrating findings from recent research, this article aims to identify key knowledge gaps and propose future directions for developing salt-resilient cotton varieties and sustainable management practices.

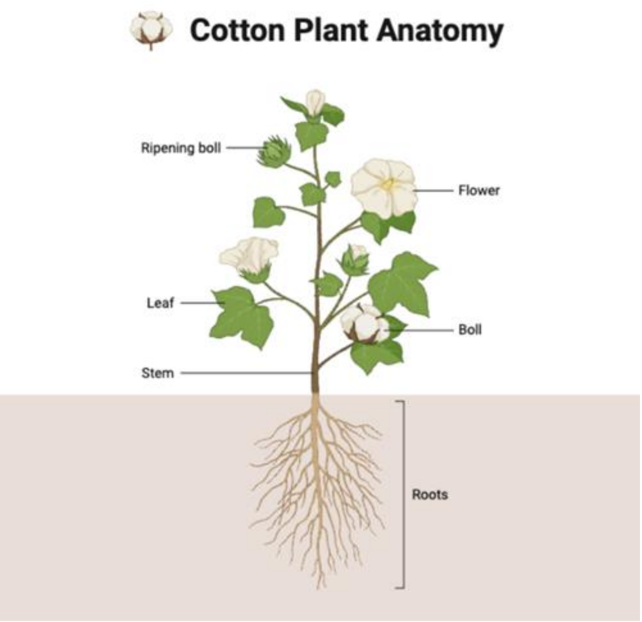

Figure 5. *Cotton plant anatomy (Mohamed et al.,2016)*

Drought stress impact on cotton

Numerous studies have studied the effects of drought stress on cotton, highlighting how it affects physiological processes, water relations, and yield outcomes. (Ephrath, 1993) shown that drought stress significantly decreases cotton's rate of photosynthesis, showing a direct impairment of the plant's basic metabolic activity when there is a water shortage. One of the main causes of the decline in growth and production during droughts is this drop in photosynthetic activity. Shalhevet, 2004 provided insight on how plants react to water shortage, pointing out that under salinity-induced water stress, cotton shows faster rates of transpiration, CO_2 uptake, and leaf extension than under pure water deficit conditions. According to the study, poor osmotic adjustment and increased root interface resistance, which impede water uptake, are responsible for the more severe impacts of water deficiency. Furthermore, a larger percentage of sugars was found in the composition of leaf sap under water stress, indicating that cotton activates osmotic control mechanisms to deal with drought. In cotton fields, remote sensing methods have been used to track abiotic conditions like drought. (Falkenberg, 2007) highlighted the value of using remote sensing to identify water stress, which may aid with timely irrigation management decisions. In a similar vein, Baker (2013) investigated the use of canopy temperature as a water deficit indication and compared several deficit irrigation scheduling techniques to maximize water use efficiency in cotton agriculture.In order to evaluate late-season drought conditions in cotton-growing regions, (Chandrasekar, 2014) used vegetation, water, and soil moisture indices for soil moisture monitoring. The significance of soil water balance models in assessing drought severity and directing irrigation techniques was highlighted by their findings. Applying exogenous substances, including glycinebetaine, has been studied as a way to lessen the consequences of drought. According to (Ahmad, 2014), using glycinebetaine enhanced water-use efficiency and prevented crop losses in situations where water was scarce, suggesting a possible agronomic intervene- tion. Drought stress has been linked to physiological reactions at the xylem level; Gitz (2015) investigated

DOI: 10.60923/issn.2281-4485/24485

the connection between gas exchange restrictions and xylem cavitation occurrences. Their research clarified the mechanisms by which drought reduces cotton productivity by suggesting that cavitation may be linked to decreased stomatal conductance and carbon absorption. To improve water use efficiency, the combined impacts of water deficit and other stresses, including the use of super absorbent polymers, have been researched. (Fallahi, 2015) discovered that applying super absorbent polymers to cotton under irrigation deficiency conditions enhanced water retention, growth, and yield, providing an acceptable approach to drought mitigation. Numerous experimental designs have been used to quantify yield responses to drought. According to lysimeter trials by (Qian, 2020), drought throughout important growth phases significantly reduced yield, with yield losses caused by drought average 2.48% per day of stress. Additionally, Xie (2021) investigated the relationship between drought and nitrogen management and found that drought conditions affected soil nitrate dynamics and cotton yield, highlighting the significance of integrated nutrient and water management strategies in water-limited scenarios.

Physiological responses and adaptive mechanisms of cotton under salt stress

Photosynthesis

Plant productivity is determined by photosynthesis, which is controlled by stomata for carbon dioxide and water exchange and photo-synthetic activity in mesophyll cells. High salinity levels reduce the rate of photosynthesis because they interfere with photosynthetic machinery and processes. Increased soil NaCl levels have been linked to osmotic stress, which inhibits cotton's ability to photosynthesize by reducing stomatal aperture size and cell expansion. The decrease in leaf surface area is the first noticeable consequence of salt stress. In the early stages, a lower photosynthetic rate per unit area is less important than a smaller leaf surface area brought on by limited cell extensibility (Shabala and Lew *et al.,* 2002). Salt stress has been shown to alter photosynthetic biochemistry and decrease photosystem activity in cotton plants by disturbing the chloroplast lamellar system, resulting in the loss of chloroplast integrity. Because stomatal closure lowers CO_2 pressure in the leaves, salt stress may indirectly affect photosynthetic enzymes. A recent study found that variations in chlorophyll ultrastructure and a decrease in chlorophyll concentrations are linked to a decline in photosynthesis. When the salt level increased, the cotton cultivars' chlorophyll concentrations (a and b) significantly decreased (Zhang, 2014b; Seemann and Sharkey, 1986; Meng, 2011). Chlorophyll concentrations could, therefore, be regarded as one of the best physiological indicators for choosing cultivars that can withstand salt. Salinity stress caused plants to express fewer genes involved in manufacturing carotenoids, which is closely related to a drop in photosynthetic rate. This ultimately had a detrimental impact on yield. Additionally, prior studies found that as salt stress increases, cotton genotypes' levels of carotenoids significantly decrease (Shah, 2017).

Concentration of inorganic ions

Three main mechanisms explain how soil salinity slows plant growth: osmotically induced water stress, specific ion toxicity from high Na^+, Cl^- ion concentrations, and nutrient ion imbalance from high sodium and chloride, which decreases the uptake of NO^{3-} , K^+, PO_4^{3-}, etc. When plants undergo exposure to salt stress, numerous studies have shown alterations in the amounts of inorganic ions. A wide range of reactions has been seen, from a sharp increase in chloride and sodium ion concentrations to a decrease in K^+, Ca^{2+}, and Mg^{2+} ions. In addition to decreasing water availability, excessive sodium ion buildup has detrimental effects on plant physiological functions. Cotton leaves were found to have a lower K^+/Na^+ ratio and a significant rise in sodium and chloride ion concentrations. While plants that could not sustain sodium homeostasis were categorized as sensitive, salt-tolerant plants managed to exclude sodium ions through their roots. Several studies indicate that maintaining the ideal ratio of K+/ sodium ions characterizes plant function during salt stress rather than sodium exclusion (Jafri *et al.,* 1995; Ding., 2010; Dai, .2014; Pervaiz., 2007). While Ca^{2+}, P, and S levels stayed constant, salinity also increased Mn, Zn, and N ions in addition to chloride and sodium ions. However, Mg^{2+}, K^+, Cu, and Fe ion concentrations were significantly reduced during salt stress. In many species, including Gossypium, chloride is more detrimental than sodium (Tavakkoli., 2010; Higbie., 2010). With a significant sodium concentration, chloride can replace bound Ca^{2+} in the cell membrane system when the sodium /Ca^{2+} ratio rises, which may damage the membrane's structural integrity and functionnality. Lastly, cellular metabolism may be affected by an abrupt rise in free Ca^{2+} in the cytoplasm (Hirayama and Mihara, 1987). Plants can adjust to salinity through various methods, including tissue tolerance to accumulated sodium and chloride, osmotic stress tolerance, and sodium and chloride exclusion. Because sodium and chloride ions compete with other nutrients, including Ca^{2+}, NO^{3-}, and K^{+}, ionic imbalance restricts the availability and transport of nutrients inside plants and lowers the Ca^{2+}, Mg^{+2} , and NPK concentration in leaves and roots (Mansour, 2005). However, several investigations have revealed that the K+, Ca^{2+} , and S levels in leaves stayed constant, leading to decreased K^{+}/Ca^{2+} or K^{+}/ sodium ratios (Munns and Tester *et al.,* 2008).

Physiological mechanisms

Succulence. In salty conditions, water-hungry plants can counteract ionic toxicity. Due to their high-water absorption, these plants are categorized as succulents (Zhu *et al.,* 2019). According to Flowers *et al.*, (1986), succulence is typically characterized by larger cells, higher leaf water content per unit area, and reduced cell suspension and growth. According to physiology, the cotton plant's high-water intake dilutes the toxic ions, giving it an excellent tolerance to salt. Plants can withstand salt stress because of their thicker leaves and larger mesophyll cells (Chaves, 2009). Because of this, there are more mitochondria, that more energy is available for Na^{+} exclusion and salt compartmentalization (Hernandez, 2000).

Specialized structures. Over time, certain halophytes have developed particular features that lessen their vulnerability to salt stress. Under saline conditions, these structures, which include salt glands, trichomes, and bladders, function as stores. In addition to succulence, cotton plants have adapted structurally to withstand salt stress by developing smaller and fewer leaves. Root lignification and wax on the plant's epidermis were two components of the salt tolerance mechanism (Parida *et al.*, 2005; Hasegawa *et al.*, 2000).

Ionic compartmentalization. Vacuoles play a central role in ionic comparison-mentalization in leaves to store salts and lower the number of toxic ions. Salt-tolerant plants may have 3 times more salt stored in their bodies than typical plants. The process of photosynthesis is not disrupted because the salt-tolerant cultivars maintain fewer harmful ions in the cytosol, which regulates the metabolic activities in the phloem and chloroplast. Additionally, it has been noted that substantial salt buildup in cells does not interfere with photosynthetic processes because of the compartmentalization of salts in vacuoles (De Araújo *et al.*, 2006; Adams. 1992; Tong., 2004). Furthermore, several pathways allow sodium and chloride ions to enter specific issues and build up without inhibiting metabolic processes. Biochemical, molecular, physiological responses of crop plants mitigate salt stress are shown in figure.6.

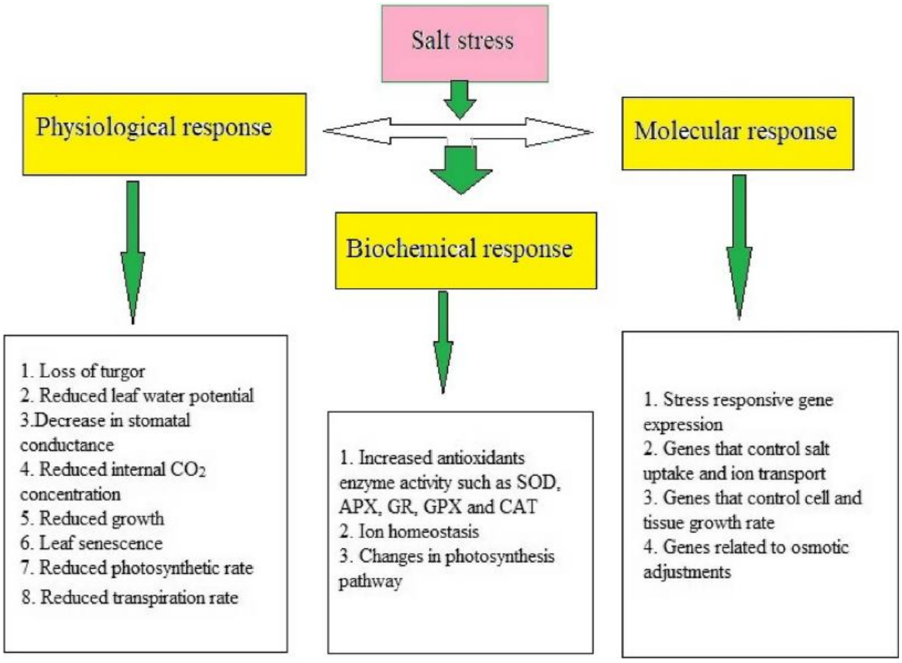

Figure 6
Biochemical, molecular, physiological responses of crop plants mitigate salt stress (Chaudhary et al., 2024).

Selective ionic transportation. Salt-tolerant cotton plants have unique pathways that allow them to take up specific ions and transfer them to various plant sections. Numerous metabolic and physiological pathways activities are interfered with when the potassium /sodium ratio deviates from normal. K^{+}/Na^{+} is transferred into plants using a variety of transporters and proton pumps. Therefore, a plant's capacity to keep potassium /sodium within its cells may be regarded as a selection criterion for saltwater tolerance. Plant antiporters are in charge of lowering potassium ion absorption and Na$^+$ toxicity in plant cells. Various ion transport mechanisms in certain plants ensure a high K$^+$ ratio, which provides salt tolerance (Salama,1994).

Compatible solutes. Water permeability in the root zone of the soil is negatively impacted by several substances, which restrict the amount of water that may reach the plants. Plants have evolved a mechanism to deal with these damages, releasing osmolytes to restore osmotic balance. By doing this, oxidative damage within the plants is decreased, and cellular sub-organelles are kept safe. Osmolytes include sugars, polyols, ammonium mannitol, amino acids, and sulfur compounds. It has been discovered that glycine, choline, proline, and polyamines help plants withstand salt stress. Tobacco tested for high salt concentrations has been shown to have a proline level that is more than 80 times higher than the control (Ray PD *et al.,* 2012; Adams,2014; Sahu.2010; Murphy,2011). Cotton has been shown to produce a significant amount of abscisic acid in response to salt stress to preserve the K$^+$/Na$^+$ equilibrium. The production of salt-tolerant cotton germplasm may result from recent developments in the crop's ability to withstand salinity (Barrett G., 2012). Numerous transcription factors thought to be significant regulators of gene expression have been discovered in the current era of molecular genetics. Many genes that are resistant to salinity have been identified in agricultural plants. However, there aren't many genes linked to salt tolerance in cotton. *ERF* is one of those mentioned (Johnson, 2003). Na$^+$/H$^+$ antiporter in tonoplasts (Wu,2004). *GhMT3a*, *ZFP*, *NAC*, *DREB*, *MPK* and *MKK* (Fan,2015; Xue,2009; Guo,2009; Meng.2009; Gao SQ, 2009; Mittova, 2000). The significance of current molecular techniques in the growth of Gossypium cultivars that can withstand salt is illustrated in Figure 7.

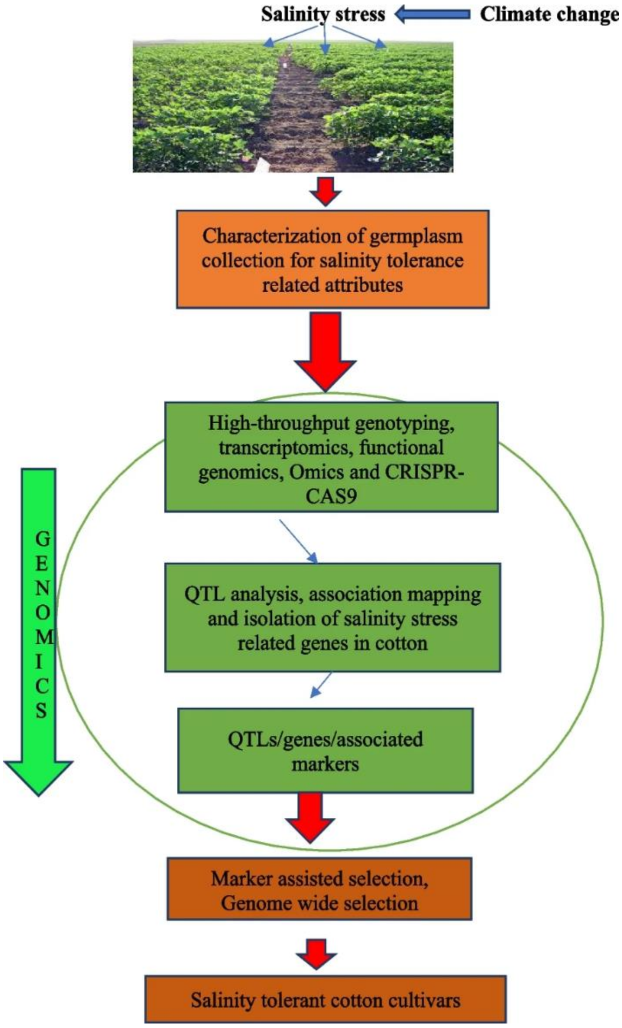

Figure 7. *A diagram of the development of Gossypium spp cultivars resistant to salinity using contemporary molecular techniques (Chaudhary, 2024).*

Agronomic management to mitigate stress in cotton under saline conditions

Mulching and furrow seeding. In salty soils, cotton plants are especially sensitive to salt stress during the emergence and seedling stages, which frequently results in poor stand establishment and seedling growth. During field management, emergence and stand establishment should receive particular attention because a successful stand establishment is essential for high cotton production. One suggested approach to reduce salt stress in cotton production is plastic mulching (Figure 8). In order to minimize direct contact between saline irrigation water and the plant root zone, it involves covering the soil surface with plastic films (Gao *et al.,* 2021). Plastic mulching decreases evaporation, improves soil water retention, and lessens the infiltration of saline water into the root zone. Additionally, plastic mulching causes an uneven distribution of salt in the soil, which effectively reduces salt damage by allowing a portion of the root system to grow in relatively low-saline soil (Bezborodov *et al.,* 2010). In salty regions, mulching protects cotton plants from suffering from salt damage. To preserve soil moisture, plastic mulching - the practice of covering a row with polyethylene film - is widespread in numerous countries. It improved, water conservation, soil temperature weed control, and saline toxicity in the root zone, which all improved plant development and cotton lint yield. Cotton plants' root systems were strengthened by plastic mulching in comparatively low-saline soil, which lessened the adverse effects that salt conditions caused to plant growth (Dong, 2010a; Dong, 2007; Dong, 2012b). Additionally, it has been shown that the combination of furrow seeding and plastic mulching improved cotton yield, stand establishment, earliness, and yield components more successfully than either method alone. The uneven distribution of salt was further enhanced by combining furrow sowing and plastic mulching. Shortly after sowing, it raised the moisture content and temperature of the soil in the root zone, which led to decreased absorption of sodium in roots and leaves, lipid per-oxidation in cotton tissues, and high Pn. It has been suggested that combining furrow bed sowing and plastic mulching is a promising method of producing cotton in saline environments (Dong, 2010; Dong, 2012b). Early mulching, which lowers moisture loss, raises soil warmth, and regulates root zone soil salt, is another potential cotton production method in saline regions (Dong, 2009). Therefore, cotton stand establishment, earliness, lint yield and plant growth may all be effectively improved by both traditional and early mulching. For stand growth, plant development, and yield, early mulching was more advantageous (Dong, 2012b). According to a study by Dong *et al.*, (2008), when plastic mulching and furrow seeding were combined, stand establishment and yield improved more significantly than when either mulching or furrow seeding was used alone (Fig. 9). Furthermore, these conditions reduced cellular damage by lowering lipid peroxidation in cotton tissues. Lastly, more photosynthesis was noted, which may have contributed to the cotton plants develop and be more productive overall. These results suggest that combining plastic mulching with furrow bed sowing is a viable method for growing cotton in saline regions.

Figure 8. *Planting flat seeds under plastic mulch (Zhang et al., 2023)*

Figure 9. *Furrow seeding under plastic mulching (Zhang et al., 2023)*

Late planting of short-season. Cotton One viable method for cultivating cotton in areas affected by salinity is the late planting of short-season cotton. In temperate regions, full-season cotton planted in saline fields typically has challenges with late maturity, poor stand establishment, and higher input costs. demonstrated that, in comparison to regular planting in a salty field, late planting of short-season cottons significantly enhanced seedling growth and seed emergence because of higher temps and lower Na+ concentrations in cotton tissues. Compared to regular-planted full-season cotton, the output from late-planted short-season cotton was more efficient in terms of earliness and required less inputs. As a result, planting short-season cotton later yields higher net returns than growing full-season cotton earlier (Dong,2010b).

Genomic function approach strategies for salt stress. Genomic function *G. barbadense* was shown to be more salt tolerant than other cultivated cotton species, although Gossypium davidsonii can withstand salt stress among wild cotton species. The D-sub genome has a significant role in *G. hirsutum's* ability to withstand salt (Li, 2014; Ahmad, 2002; Zhang, 2016). To develop salt-tolerant genotypes, the researchers have tried to modify the genes involved in the molecular processes that respond to salt stress (Table. 1). Cotton

Table.1 *Functional genomics of salt responsive genes in cotton*

Functional study	Genes	Cotton species (cultivar)	Growth stage(tissue)	References
ERF-encoding gene	GhERF2	G.hirsutum (Zhongmian12)	Mature plant (cotyledon, embryo, leaves, roots, stem and flower)	Jin et al., (2010)
ERF-encoding gene	GhERF3	G.hirsutum (Zhongmian12)	Mature plant (stem, roots, flowers, and leaves)	Jin et al., (2010)
ERF-encoding gene	GhERF6	G.hirsutum (Zhongmian12)	Mature plant (cotyledon, flower, roots, stem and leaves)	Jin et al., (2010)
ERF-encoding gene	GhERF38	G.hirsutum (Coker 312)	Seedling (Cotyledon, hypocotyls, roots and leaves)	Ma et al., (2017)
bZIP-encoding gene	GhABF2	G.hirsutum (Simian3)	Seedling (leaves, roots, stem)	Liang et al., (2016)
Annexingene	GhAnn1	G.hirsutum (7235)	Seedling(leaves)	Zhang et al., (2015)
EncodeNACdomain	GhNAC1–GhNAC6	-	G.hirsutum	Shah et al. (2013)
EncodeNACdomain	GhNAC4,GhNAC6	G.hirsutum (Jinmian 19)	Seedling(leaves)	Meng et al., (2009)
Mitogen-activated protein kinase	GhMKK1	G.hirsutum (Lumian 22)	Seedling (cotyledon leaves, roots and stems)	Lu et al., (2013)
WRKY transcription factor	GhWRKY11 GhWRKY12 GhWRKY13	G.hirsutum (Coker 312)	Seedlings(roots)	Zhou et al., (2014)
WRKY transcription factor	GhWRKY39	G.hirsutum (Lumian 22)	Seedling (leaves, roots and stems)	Shi et al., (2014b)
WRKY transcription factor-encoding	GhWRKY39-1	G.hirsutum (Lumian 22)	Seedling	Shi et al., (2014a)
WRKY transcription factor-encoding	GhWRKY41	G.hirsutum (Lumian 22)	Seedling (leaves, roots, stem)	Chu et al., (2015)
WRKY transcription factor-encoding	GhWRKY25	G.hirsutum (Lumian 22)	Seedlings (leaves, stem, roots)	Liu et al., (2016)
Trehalose-6-phosphatesynthase (gene)	GhTPS11	G.hirsutum (ZM19)	Seedling (Cotyledon, stem, roots)	Wang et al., (2016)
Drought induced protein which is Cys2/His2zinc-finger proteins	GhDi19-1 GhDi19-2	G.hirsutum (Xuzhou 142andCoker312)	Seedling (Cotyledons, roots)	Li et al., (2010)
Mitogen-activated protein kinase gene	GhMAP3K40	G.hirsutum (Lumian 22)	Seedling (leaves, roots and stem)	Chen et al., (2015)
Superoxide dismutase	GhSOD1	G.hirsutum (Zhongmiansuo3)	Mature plant (stems, leaves and ovules)	Luo et al., (2013)
Tonoplast Na$^+$/H$^+$antiporter	GhNHX1	G.hirsutum (ZM3)	Seedling (cotyledon, leaves, stem, roots)	Wu et al., (2004)
Dehydration-responsive element-binding protein gene	GhDREB	G.hirsutum (Simian3)	Seedling(leaves)	Gao et al., (2009)
Cold-circadianrhythm-RNA binding-like protein	GhCCL	G.hirsutum (Bikaneri Narma)	Germination	Dhandapani et al., (2015)

germplasm contains plenty of variety, and studying it could result in the development of cultivars that can withstand salt. It is believed that transcription factors are important modulators of gene expression. Few salt-resistant genes have been found in cotton, even though many salt-responsive genes have been found in other plants e.g. *ZFP , MKK, ERF, NAC, DREB, MPK, GhMT3a* and tonoplast H+/Na$^+$ antiporter (Wu,2004; Guo, 2009; Lu, 2013; Johnson,2003; Zhang, 2011; Gao, 2009;Xue, 2008).

Plant density management. Improved plant density under saline stress significantly boosted cotton yield, according to numerous previous experiments (Feinerman, 1983). Excessively saline soils typically inhibit plant development and size. Since plants are smaller, there is more room between their canopies for other plants to flourish. According to reports, cotton's earliness was improved by growing plant populations (Fowler and Ray, 1977). Dong *et al.,* (2012a) came to the conclusion that, in situations with high salinity, increasing plant density significantly increases the yield of seed cotton. It is proposed that in heavily salinized fields, more plant density would be required to improve cotton yield and earliness.

Increasing soil moisture and temp. It has been determined that improving soil warmth and moisture under salinity stress conditions improves seed emergence and seedling growth. planted cotton seeds in pots with varying amounts of saline soils that were taken from saline areas in the Yellow River Delta with varying moisture contents (12, 16, and 18%). They found that as soil moisture levels increase, so does seedling emergence and growth. Improved seedling emergence and growth were the results of the increased moisture content, which also reduced osmotic stress and Na^+ buildup in leaves and lessened the salt toxicity effect. Another study by Dong *et al.,* (2012c) showed that soil temps between 20 to 30°C are favorable for growth under salinity stress and seedling emergence by sowing cotton seeds in potted saline soils at different dates to assess the impacts of soil temperature (Dong, 2012c; Dong, 2012b).

Water management strategies. Low-quality irrigation water with high (SAR), (RSC), EC and pH value - all of which contribute to salinity stress - reduces cotton plant development. Therefore, to successfully cultivate cotton under salinity stress, a prudent approach to water management is essential. Because it drains away or leaches down soluble salts from the root zone, using high-quality water is essential for improved plant growth and soil management, production in a saline climate. Crop fields should be irrigated using surface water rather than salty subsurface water. It is recommended to utilize gypsum in salty subsurface water since it has been shown to boost grain yield in wheat and rice. Additionally, using gypsum with surface irrigation water lowers the pH, SAR and ECe of soil at depths of 0 to 30 cm (Mehdi, 2013; Murtaza, 2006; Ezeaku,2015).

Fertilizer management. In order to mitigate the adverse effects of salt on Gossypium spp crops while preserving an ideal nutrient balance, it is essential to implement efficient fertilizer and plant nutrition management systems. Fertilizers can mitigate nutrient imbalances brought on by salt stress and promote balanced nutrient up-take by selective application. Several studies have shown that, in saline environments, balanced fertilization with NPK enhances cotton production and quality (Isae,2021; Ganiev,2021). Further, it has been determined that micronutrients like Zn and B are important for improving cotton's resistance to salt. Fertigation methods, like as controlled-release fertilizers and drip irrigation have been used to ensure accurate nutriation delivery while reducing salt stress. These techniques assist cotton development in saline environments by improving the effective uptake of vital nutrients (Ahmad,2018; Rahman,2019). Enhancing cotton's ability to withstand salt requires maintaining sufficient amounts of important macronutrients, such as NPK, as well as micro-nutrients, such as Zinc and iron. Sufficient nitrogen intake is essential for controlling osmotic potential and preserving ion homeostasis, which lessens the adverse effects of salt (Isae,2021; Hassan,2020). Cotton's resistance to salt stress is improved by phosphorus, which plays a major role in energy transfer and carbon metabolism. Furthermore, potassium supplementation increases the activity of antioxidant enzymes and promotes osmotic adjustment. Calcium and sulfur also help cotton tolerate salinity (Khan,2019; Zeng,2020). It has been demonstrated that adding organic amendments, such farmyard manure and compost, enhanced nutrient availability, water retention capacity and soil structure - all of which help cotton plants tolerate higher saline levels. Furthermore, gypsum and calcium and magnesium-rich amendments can be applied to improve soil structure and reduce sodium uptake, which will help cotton tolerate salt better (Abbas,2021). According to research, applying nitrogen early in the irrigation cycle increases production and improves the efficiency of fertilizer use. Additionally, it has been shown that applying K increases cotton yield and growth, especially in salty soils. Additionally, it has been noted that elevated saline levels significantly reduce plant growth metrics; however, this adverse effect can be lessened by applying $NH4NO^{3-}$ or KCl via foliar spray. It has been demonstrated that foliar fertilizer spray helps cotton grow and develop in saline environments.

Utilization of root-associated microorganism. The ability of microorganisms to reduce salt stress and increase the production of cotton has drawn more attention recently. By colonizing the plant roots, these advantageous bacteria improve water absorption, nutrient uptake, and hormone regulation, helping plants better withstand the effects of salinity stress. Cotton production in saline environments can be greatly improved by using microorganisms as bioinoculants. According to Liu *et al.,* (2016), (AMF) can increase the uptake of Zn and P while supporting the buildup of leaf proline. But it's crucial to remember that, in comparison to AMF species from non-salty soil, Glomus mosseae, which was isolated from saline soil, is less successful in reducing salt stress (Evelin, 2009). The indole hormone melatonin can mitigate the adverse effects of salt stress (Jiang, 2021; Egamberdieva, 2015; Kang, 2022). Seed inoculation is a crucial method of using microorganisms to lessen cotton's exposure to salinity stress. Cotton plants' ability to withstand salt has been demonstrated to be enhanced by seed inoculation with PGPR strains like *Pseudomonas, Azospirillum or Bacillus* . By forming a symbiotic association with the plant roots, these bacteria promote root development and improve nutrient uptake. In the end, this results in increased (plant productivity and growth in saline environments (Sarwar,2019). (Islam,2017) have shown that inoculating seeds with PGPR improves cotton yield and growth in saline environments. Some plant growth-promoting rhizobacteria strains, for example, can fix atmospheric nitrogen, solubilize phosphorus, or generate compounds like (IAA) that promote plant development. The plant's capacity to tolerate salt stress is increased by these actions, which also raise hormone levels and nutrition availability. Investigations by (Khan,2016) demonstrated that the use of PGPR as a soil supplement greatly enhanced cotton production, growth, and nutrient uptake in saline environments. Furthermore, cotton production under salt stress may profit even more from the use of microbes in conjunction with other mitigating techniques, such as the application of organic fertilizers. Studies have shown that the combined effects of microorganisms and organic amendments can improve cotton production and development in saline environments (Nouman,2018). Therefore, a promising way to decrease salt stress and increase cotton yield is through microorganisms, especially strains of PGPR. Beneficial microbes that improve water absorption, nutrient uptake and hormone regulation. Including microorganisms in sustainable cotton production systems can help develop resilient farming methods that address the problems caused by salinity stress (Zhang,2023).

Drip irrigation and its role in salinity management. Drip irrigation is a highly efficient water delivery system that applies water directly to the plant root zone, lessening evaporation and runoff losses. This practice is particularly effective in saline settings because it lessens salt build-up in the root zone and maintains optimal soil moisture levels. Unlike drip irrigation, which often leads to salt build-up on the soil surface due to evaporation, drip irrigation enables localized leaching of salts away from the root zone, thus helping crops tolerate saline conditions better. Additionally, when integrated with fertigation, drip irrigation systems improve nutrient-use efficiency and improve crop yield under salinity stress. However, adoption in developing regions may be limited due to high initial costs, maintenance requirements, and lack of technical knowledge (Culas *et al.,* 2020).

Biochar and its role in salinity stress management. Biochar, a carbon-rich by-product obtained from the pyrolysis of organic biomass under low-oxygen conditions, has gained significant attention as a sustainable soil amendment for improving soil quality and mitigating abiotic stresses such as salinity. When applied to saline soils, biochar improves soil structure, enhances nutrient availability and increases water-holding capacity thereby decreasing salt-induced osmotic and ionic stress on plants. It also influences soil microbial activity and helps in binding Na^+ ions, leading to better soil CEC and decreased (EC). Studies have shown that BC application enhanced crop yield and plant growth under saline environments, especially when combined with inorganic or organic fertilizer. However, scalability and economic feasibility remain concerns, particularly in low-income agricultural systems, transportation logistics and due to variability in feedstock, production costs (Akhtar,2015).

Crop rotation. In order to enhance soil health, nutrient balance, and crop yield, different crops are grown in rotation on the same field over the course of several seasons or years. The practice is known as crop rotation. Because legumes fix atmospheric nitrogen and increase nitrogen availability for succeeding crops, rotating crops, such as cotton with legumes (such as soybean or alfalfa), improves soil fertility (Karlen *et al.,* 1994). Additionally, through promoting better root penetration and soil aggregation, crop rotation can improve soil structure, increase organic matter content, decrease pest and disease accumulation, and improve salt leaching efficiency in saline soils (Bullock, 1992; Rengasamy, 2010).

Seed priming. A pre-sowing method called "seed priming" improves seed performance and, eventually, increases the production of crops in a variety of ecologically difficult conditions. Due to its detrimental effects on cotton growth, development, and yield, salinity stress is a significant problem in cotton production. Nonetheless, seed priming has become a viable strategy to reduce salt stress and boost cotton yield. Using plant growth-promoting rhizobacteria (PGPR) as seed inoculants is another method of seed priming for reducing salinity stress. PGPR efficiently colonizes plant roots and enhances hormone control, water retention, and nutrient uptake, resulting in improved crop performance under salinity stress. For example, a study by Luqman *et al.,(*2025) found that by increasing root length, shoot height, and biomass yield, seed inoculation with PGPR strains such Azospirillum and Azotobacter improved salt tolerance in cotton. Additionally, cotton salinity stress can be lessened by priming seeds with particular chemical compounds. For instance, it has been discovered that priming seeds with antioxidants such α-tocopherol (TOC) and ascorbic acid (ASA) lessens the detrimental effects of salt stress by preventing oxidative damage and preserving cellular

DOI: 10.60923/issn.2281-4485/24485

homeostasis. Adrees *et al.* (2018) discovered that in saline cotton, seed priming with ASA and TOC enhanced germination, seedling growth, and physiological characteristics.

Flat-sowing technique. The flat (level-ground) planting (with irrigation borders) technique, which was once traditional for some grain and forage crops, is quickly becoming widely used among cotton growers in some US cotton-producing regions (the Sun Belt). This is due to the perceived advantages of cost and water savings on leased farmlands where drip irrigation is not feasible, convenient mechanical harvesting that does not require row-end plow down as in raised-bed planted cotton harvesting, less cultivation and tillage requirements, and a faster soil temperature rise for sowed seeds. The majority of the areas farmed using this method have been laser levelled see figure 10. Farmers use tractors to apply the first dosage of fertilizer, then fertigation for any additional fertiliser applications. They merely clean the field boundaries between crops and do not disrupt them in between harvests. (Adeleke *et al.,* 2024).

Ridge-planting technique. An agronomic technique known as "ridge planting" involves planting crops on raised soil ridges rather than on flat ground. The ridges, which are typically 15 to 30 cm high, enhance root development, aeration, and drainage. By using furrow irrigation to transport salts away from the seed and young roots, this technique lessens the buildup of salt around the root zone in salty soils. Therefore, in salt-affected environments, ridge planting improves root development, nutrient uptake, and total yield of crops.Ridge-furrow planting is another important cotton sowing method that is utilized all over the world (Farooq *et al.,* 2020) This method involves planting cotton seeds in ridges made by mechanical ridgers (Fig. 11a) or during the cultivation of earlier growths (Fig. 11 b).

Figure 10. *A typical flat-row cotton field with irrigated boundaries on a US farm. For the flat planting method, the majority of farmlands are laser levelled, and the borders are left unaltered in between reaping to maintain the levelling (Adeleke et al., 2024).*

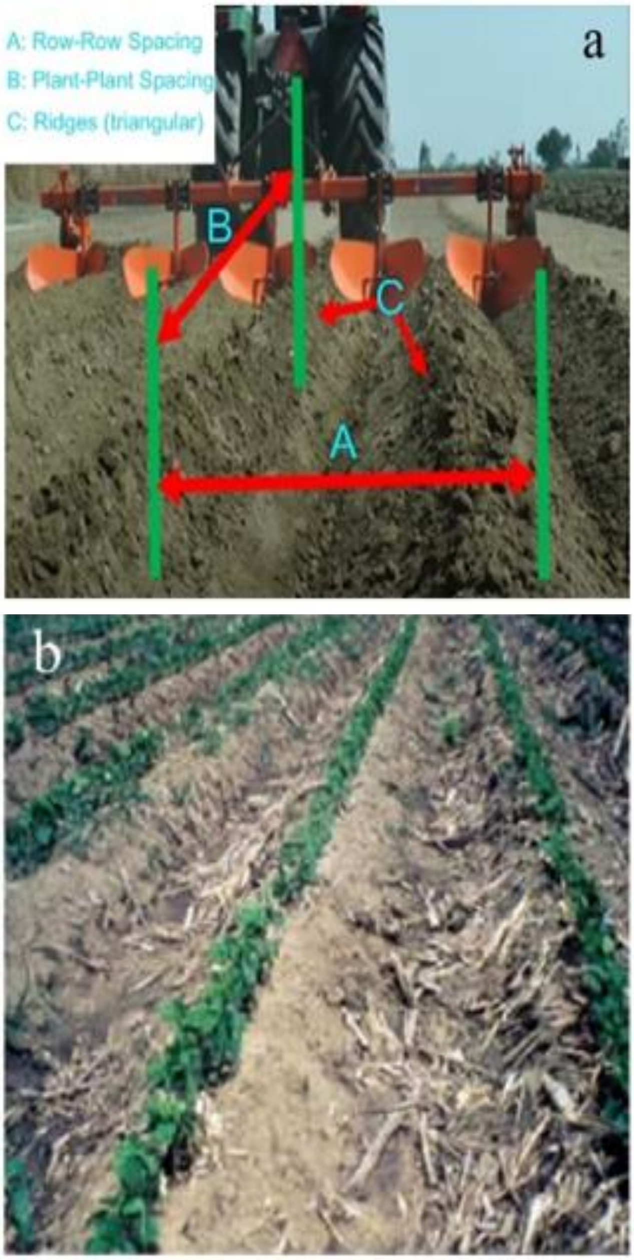

Figure 11a and b. *Cotton ridge-planting method: (a) A five-row ridger makes new ridges in a cotton field with general planting geometry shown. (b) Ridge-sowing fields that are farmed with new crops while the growth and crop residue from the previous year stay in the furrow, aiding in the management of erosion. Typically, row-crop rotating ridge-sowing fields may have 30% to 50% nonuniformly distributed residue (Adeleke et al., 2024)*

DOI: 10.60923/issn.2281-4485/24485

Table 2. *Literature review: Salinity stress mitigating strategy in cotton (1987-2025)*

Author(s)	Mitigation strategy	Key findings
Li, 2022; Singh, 2022	Silicon application	The Si application strategy enhanced antioxidant activity, photosynthesis and reduced sodium toxicity in cotton under salinity stress.
Saleem, 2021 Luqman, 2025; Akbar, 2022	Plant growth–promoting rhizobacteria (PGPR)	Plant growth–promoting rhizobacteria improved root development, nutrient uptake, and increased cotton tolerance to saline soil environments.
Rezaee, 2015	Salt-tolerant cotton cultivars	Salt-tolerant genotypes showed enhanced physiological responses and better yield stability under saline settings.
Nazir, 2014; Nazir, 2023; Kaur, 2025)	Seed priming with salicylic acid	Seed priming enhanced antioxidant enzyme activity, germination rate and early seedling vigor under salt stress.
Yang, 2019; Li, 2024; Soignier, 2024 Lin, 2025	Subsurface drainage and irrigation management	Enhanced drainage systems significantly decreased soil salinity and improved cotton yield in saline soils.
Jia, 2024; Li, 2023	BC soil amendment	Biochar (BC) enhanced soil physico-chemical properties and alleviated salinity stress in cotton cultivation.
Heng, 2021	Drip irrigation management	Drip irrigation decreased salt accumulation in the root zone and enhanced water use efficiency in cotton fields.
Zain, 2017; Shao, 2024; Bar-Tsur, 1987	Potassium fertilization	Potassium (K^+) nutrition improved osmotic adjustment and decreased Na^+ toxicity in cotton plants.
Abid, 2024	Gypsum application	Gypsum significantly enhanced soil structure and decreased sodicity in saline–alkali soils used for cotton production.
Yang, 2021	Integrated management (drainage + salt-tolerant varieties)	Integrated soil and crop management strategies enhanced soil reclamation and cotton productivity in saline settings.
Maratovna et al., 2026	Bio-fertilizer	The investigation shows that biofertilizer-based methods support long-term soil fertility, ecological stability, and sustainable cotton production in addition to helping to gradually desalinate soils.
Li et al., 2026	Brackish water + nitrogen	To determine the right combination of nitrogen to water salinity for maximum production and efficiency, the researchers used advanced optimization techniques (such as AI models).
Ma et al., 2026	Drip irrigation + nitrogen	Increase cotton yield, enhance nitrogen use efficiency, avoid wasting fertiliser, and decrease environmental pollution.
Gao, 2026	Side soil covering	In DSWE, side soil covering (SSS) combined with minimal irrigation can save up to 70% of water while preserving healthy cotton growth.
Guo, 2026	ZNPs	Our research offers a comprehensive understanding of Zinc nano particles-mediated salt tolerance and a strategic basis to develop agronomic techniques based on nanoparticles to increase crop tolerance in saline conditions.
Sarioğlu, 2026	BC	By analyzing its effects on physiological development metrics, oxidative stress indicators, and soil microbial activity in greenhouse settings, this study sought to determine how effectively tobacco-derived biochar mitigated salt stress in cotton.
Derbew, 2026	Moderate irrigation	For cotton, moderate irrigation (approximately 450 mm) is good since it balances soil bacteria, salt, and water, increasing production.
Liu, 2026	Water and nitrogen	Overall, these results offer empirical support for the management strategies already in place in Xinjiang and quantitative recommendations for enhancing water and nitrogen management to increase cotton productivity.
Lu, 2026	Bio-fertilizer + nitrogen	Even when using saline water for irrigation, cotton productivity and effectiveness are improved by using biofertilizer with lower nitrogen.
Zhang, 2026	irrigation	In conclusion, by improving water retention capacity and promoting salt leaching, optimizing irrigation techniques (providing 15 mm of water on both the first and eighth days after planting) enhanced soil water-salt distribution in the 0–20 cm soil layer, raising cotton emergence rates. In cotton fields in southern Xinjiang, this work offers theoretical and practical foundations for water-saving irrigation and water-salt management.

Table 2 (continued). *Literature review: Salinity stress mitigating strategy in cotton (1987-2025)*

Author(s)	Mitigation strategy	Key findings
Xia,2026	Deep vertical rotary tillage + Bacillus subtilis	In saline-alkali land, deep tillage (DVRT) when combined with beneficial bacteria (Bacillus subtilis) significantly enhances soil quality and cotton yield.
Tadjiev,2026	Zig-zag furrow irrigation	The yield of seed cotton rose by 0.32–0.43 t ha^{-1}, and water use efficiency improved from 1902 m^3 t^{-1} to 1426 m^3 t^{-1}.
Gu,2026	Plastic mulching film	The study supports policy for integrated agricultural and ecological development by offering a scientifically validated approach to PMF promotion that a balance between yield increase and environmental sustainability.
Kassa,2026	Cover crops + crop rotation and pest management	Our results highlight the need for sustainable pathways that can enhance both financial and environmental performance, such as crop rotation, cover crops, integrated pest management, and supplemental irrigation, as well as policy incentives like Australia's Nature Repair Market.
Zhang,2026	BC	The beneficial effects of biochar on cotton yield and yield components in reducing drought stress have been shown in this paper, setting the stage for further research into its applicability in cotton production in semi-arid and arid regions.
Wu,2026	CO$_2$-irrigation	Our results show that CO$_2$-enriched irrigation improves nutrient availability and the rhizosphere microenvironment, offering a new route for carbon recycling and high-efficiency cotton production in arid areas.
Kökce,2026	Trichoderma, particularly Tr125	Cotton can withstand disease and thrive in salty soils by using helpful fungus (Trichoderma, especially Tr125).
Yi,2026	magnetized brackish water	Cotton productivity and efficiency are increased and soil salinity is decreased by using magnetized brackish water, especially throughout the growing season.
Ullah,2026	S. caprae DS-2 and P. hunanensis RT-12	These results highlight the potential of S. caprae DS-2 and P. hunanensis RT-12 as a bioinoculant consortium for long-term salt stress reduction in the cultivation of cotton.
Liang,2026	Pseudomonas aeruginosa A10 rhizobacteria	They concluded that Pseudomonas aeruginosa A10 rhizobacteria enhance cotton growth under NaCl stress.
Gao,2021; Wang,2018	Plastic mulching	Improving soil water retention reduces evaporation and reduces root zone salt accumulation.
Zhang,2023	Concave and convex cultivation	Facilitates cotton seedling emergence enhance drainage
Sarwar.2019; Islam,2017; Shi,2020; Nouman,2018	Utilization of root-associated microorganism	Alleviating salinity stress enhances cotton productivity
Abrol.1988; Dong.2008	Furrow seeding	Unequal salt distribution in the root zone.
(Dong,2010)	Delayed planting	Promotes water absorption, decreases ionic toxicity
Hossain,2023	BC	Improves soil properties, enhances salt tolerance, and increases yield
(Ashraf,2010)	Increase in seeding rate and plant density	Enhances plant growth improve production, and promotes earlier cotton maturation
Isaev,2021; Ganiev,2021; Ahmad.2018; Hassan,2020; Abbass.2021	Fertilizer management	Promotes balanced nutrient uptake; decreases toxicity, improved cotton salinity tolerance
Du,2015	Drip irrigation	Promotes flower bud development, reduces early shedding. Increases boll weight and boll number; prevents stress-related boll drop. Improves water and fertilizer use efficiency; reduces soil salinity build-up.
Bullock, 1992; Rengasamy, 2010; Karlen et al., 1994	Crop rotation	Improved soil health and organic matter, and reduced soil salinity and pest disease

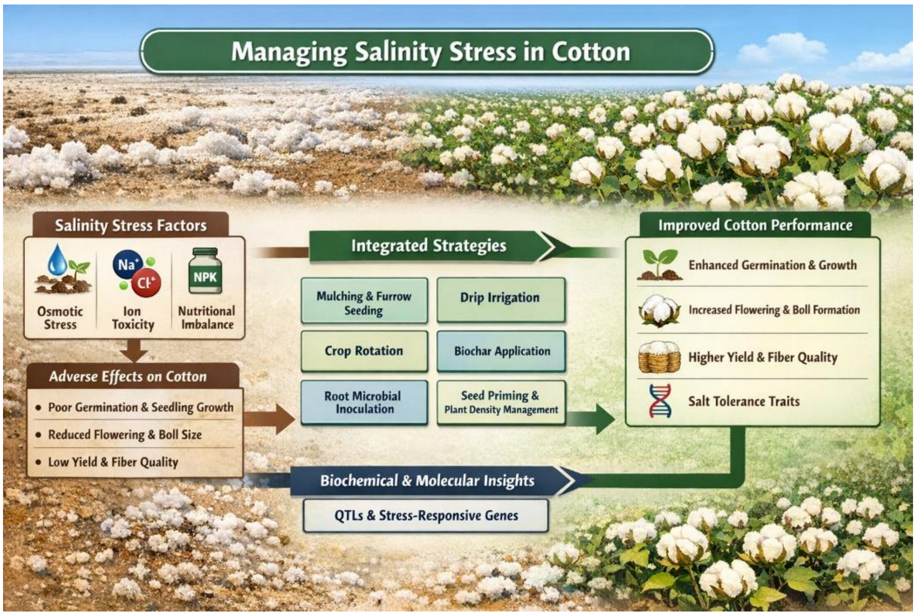

Figure 12
Flow chart diagram

Comclusions: summary and prospects

Salinity affects more than 800 million hectares of arable land worldwide. 25% of China's cropland is made up of saline-alkali soils, which are underutilized (Liu *et al.,* 2021). More than half of the world's countries suffer from salinity, making it an essential problem for maintaining food security. Saline areas make up about 23% of all agricultural land worldwide. Thus, cotton production in saline lands has a lot of guarantees, but it mostly depends on research and technological advancements in cotton cultivation in saline soils. Although improvement in salinity tolerance of cotton through genetic breeding is believed to be a potentially useful approach to mitigating salinity stress, agronomic practices that improve at least part of the root-zone environment reduce salinity effects. Agronomic practices improved cotton productivity in saline soils. Specific ion toxicity, somatically induced water stress, and nutritional imbalance brought on by salt stress have a negative impact on development and plant growth and, eventually, crop establishment. Salt stress alters enzyme metabolism, inhibits the absorption of nutrients, and causes nutritional problems, all of which lower yield and degrade fiber quality. Salt-tolerant genotypes could be developed efficiently using the current genetic diversity. Agronomic techniques that enhance at least a portion of the root-zone environment are more practical methods to lessen the impacts of salinity, even though genetic breeding is seen to be a potentially helpful strategy for improving cotton's tolerance to salinity. In conclusion, this review has highlighted the integrated agronomic strategies for alleviating salinity stress and enhancing cotton yield. Second, it's important to investigate how nutrient management and soil amendments can reduce salinity stress in cotton. It has been demonstrated that soil amendments, including gypsum, organic matter, and zeolite, enhance soil structure and water-holding capacity, hence mitigating the detrimental effects of salinity on cotton. Cotton growth and production can also be improved in saline environments by optimizing nutrient management techniques, such as balanced fertilization, micronutrient supplementation, and effective irrigation (Zhang *et al.,* 2020). Further, the development and application of precision agriculture technology for saline cotton fields should be the main emphasis of future study. In order to identify early indicators of saline stress in cotton and enable focused interventions, remote sensing methods like hyperspectral imaging and thermal imaging can be used (Yang *et al.,* 2020). Furthermore, by combining sensor-based irrigation systems with decision support tools, water and nutrient management can be optimized to meet the unique requirements of cotton plants under salt stress (Zhang *et al.,* 2019).

Declaration of competing interest: N/A

Fund: Not applicable

Data availability statement: Not applicable

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Abbreviation

AMF = Arbuscular Mycorrhizal Fungi
APX = Aascorbate Peroxidase
ABA = Abscisic Acid

CAAS = Chinese Academy of Agricultural Sciences
CRISPR = clustered regularly interspaced short palindromic repeats
CAM = Choline Monooxygenase
CAT = Catalase
DAPs = Differentially Abundant Proteins
EC = Electrical Conductivity
Ece = Saturated paste extract
ERS = Electromagnetic radiation spectrum
DHA = Dehydro-ascorbate Reductase
GR = Glutathione Reductase
GPX = Guaiacol Peroxidase
HAK5 = High Affinity K^+ *transporter*
HDR = Homology-Dependent Repair
HO• = Hydroxyl radical
JA = Jasmonic Acid
LSCB = Subtending lLeaf of Cotton Boll
MDAR = Monodehydroascorbate Reductase
MAS = Marker-Assisted Selection
NO = Nitric Oxide
POD = Peroxidases
QTL = Quantitative Trait Loci
SOS = Salt Overly Sensitive
SOD = SuperOxide Dismutase
SA = Salicylic Acid

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