*agronomy*

*Review*

# Mitigating Salinity Stress and Improving Cotton Productivity with Agronomic Practices

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**Abstract:** In saline and salinity-affected soils, the global productivity and sustainability of cotton are severely affected by soil salinity. High salt concentrations hinder plant growth and yield formation mainly through the occurrence of osmotic stress, specific ion toxicity, and nutritional imbalance in cotton. A number of agronomic practices have been identified as potential solutions to alleviate the adverse effects induced by salinity. While genetic breeding holds promise in enhancing the salinity tolerance of cotton, agronomic practices that improve the root zone environment, ameliorate soil conditions, and enhance salinity tolerance are currently considered to be more practical. This compressive review highlights the effectiveness of agronomic practices, such as furrow seeding, plastic mulching, their combination, densely planting, and the appropriate application of fertilizer and plant growth regulators, in mitigating the negative impact of salinity on cotton. By implementing these agronomic practices, cotton growers can improve the overall performance and resilience of cotton crops in saline and salinity-affected soils. This review provides valuable insights into practical agronomic measures that can be adopted to counteract the adverse consequences of soil salinity on cotton cultivation.

**Keywords:** cotton; salt stress; agricultural measure; root zone

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## 1. Introduction

Soil salinity is a pervasive agricultural limitation affecting a substantial portion of cultivated land and irrigated areas worldwide [1]. Despite cotton's reputation as one of the more tolerant major crops to salt stress [2], excessive soil salinity has detrimental effects on plant growth, development, yield, and fiber quality [3,4]. The salt content in soil is commonly indicated by measuring the electrical conductivity of a saturated paste extract (ECe). Saline alkali soil typically has an ECe value higher than 4 dS $m^{-1}$ at 25 °C. Salinity levels are categorized as low (4–8 dS $m^{-1}$), moderate (8–12 dS $m^{-1}$), and high ($\geq$12–16 dS $m^{-1}$) [5]. Salinity stress typically hampers germination and emergence rates, inhibits shoot growth, and ultimately reduces seed cotton yield and fiber quality [6,7]. However, the extent of these negative impacts on plant growth and yield varies with different salinity levels, resulting in yield reductions of 10%, 25%, and 50% at ECe levels of 10, 12, and 16 dS $m^{-1}$, respectively [8,9]. Over the past few decades, numerous studies have investigated effective practices to mitigate the adverse effects of salinity, leading to advancements in the understanding of salt stress–cotton interactions [10–13]. This paper addresses pertinent literature related to the management of salinity stress on cotton growth and yield, emphasizing the utilization of holistic agronomic strategies.

## 2. Negative Impacts of Salinity on Cotton

Cotton, despite its classification as moderately tolerant to salt stress (7.7 dS $m^{-1}$), experiences decreased plant growth, boll number per plant, and seed cotton yield under salinity conditions. An understanding of the adverse effects of soil salinity on cotton is crucial for effective management. Salinity impacts are observed across various growth stages of field-grown cotton, including germination, seedling, vegetative, and maturity stages. However, the emergence and young seedling stages are particularly susceptible to salinity stress compared to other stages [11]. High soil salinity levels commonly result in delayed and reduced seed germination and emergence in cotton [3], as well as abnormal plant growth characterized by stunted root and shoot development. Salinity stress negatively impacts the biological or economic yield of cotton, which can be attributed to various physiological and biochemical processes at the cellular and molecular levels [14,15].

It is generally believed that soil salinity stress adversely affects plant growth and cotton yield through three primary pathways. Firstly, excessive salt concentration induces osmotic water stress. Secondly, the presence of high levels of sodium and chloride ions causes specific ion toxicity. Finally, the abundance of $Na^+$ and $Cl^-$ ions disrupts the balance of nutrient ions, resulting in the reduced uptake of essential ions such as $K^+$, $NO_3^-$, $PO_4^{3-}$, and others [16].

### 2.1. Salinity-Caused Osmotic Stress

Salinity in the soil environment results in excessive salt content, which reduces the osmotic potential of the soil solution. As a consequence, cotton plants are unable to sufficiently take up water, leading to hindered plant growth and development due to osmotic effects [17]. High salinity levels disrupt the osmotic balance in cotton plants, leading to reduced water uptake, decreased osmotic potential, and hindered leaf expansion [18]. The cellular and metabolic mechanisms involved in osmotic stress caused by salinity are similar to those observed in drought stress [19]. The production rate of new leaves heavily relies on the water potential of the soil solution, much like in plants experiencing drought stress [15]. The decrease in leaf and root growth rates can be attributed to water stress-related factors [20]. The extent of growth inhibition resulting from osmotic stress is influenced by the timing and scale of the response, the specific tissue and species being examined, as well as the rate at which stress is imposed, either abruptly or gradually [20]. Transcript-profiling studies have indicated that plants rapidly modulate gene expression along with physiological and biochemical changes in response to both mild to moderate drought and salt stress [15]. Notably, under salinity, a larger number of genes were affected more prominently compared to drought stress, likely due to the combined effects of dehydration and osmotic stress in salt-stressed plants [21].

### 2.2. Salinity-Caused Toxic Damage

The excessive uptake and accumulation of toxic ions such as sodium (Na+), chloride ($Cl^-$), and sulphate ($SO_4^{2-}$) in cotton plants originating from saline soil or irrigation water can induce toxicity [2]. Although chloride and sulphate are necessary for plant growth, their concentrations in saline soil surpass the levels required for normal plant development. Plants absorb and accumulate salts in their transpiring leaves through their roots [20]. Prolonged accumulation of these salts in transpiring leaves eventually leads to leaf injury, primarily resulting from exceedingly high concentrations of $Na^+$ and $Cl^-$ [22]. The injury is believed to occur when the salt load exceeds the cell's capacity to compartmentalize salts in the vacuole. Consequently, salts rapidly accumulate in the cytoplasm, inhibiting enzyme activity [23]. Alternatively, salts could accumulate in the cell walls, causing cellular dehydration [22]. Concentrations of $Na^+$ and $Cl^-$ in cotton roots, xylem sap, and leaves increase with the rising concentration of NaCl in the soil [24]. This influx of $Na^+$ and $Cl^-$ disrupts the ion balance in the cytoplasm, particularly the $Ca^{2+}$ balance. Elevated levels of $Na^+$ can displace bound $Ca^{2+}$ in the plasma and cell membrane systems, increasing the $Na^+/Ca^{2+}$ ratio and ultimately damaging the membrane's structural integrity and functionality. Consequently, there is a significant increase in free cytoplasmic $Ca^{2+}$, impairing cellular metabolism [24].

### 2.3. Salinity-Caused Nutrient Disturbance

Salinity can disrupt the uptake and utilization of essential nutrients in plants due to competition and interactions between soluble salts and mineral nutrients [23,25]. The accumulation of $Na^+$ and $Cl^-$ and the reduced uptake of other mineral nutrients, such as $K^+$, $Ca^{2+}$, and $Mn^{2+}$, can result in an ionic imbalance within cells [26]. A high $Na^+/K^+$ ratio, caused by the buildup of sodium ions, leads to enzyme inactivation and affects metabolic processes in plants [27]. $Ca^{2+}$ is believed to play a crucial role in mitigating salinity damage by preserving the cell membrane structure in cotton. Cramer (1987) found that salt stress significantly impairs the absorption, transportation, and distribution of $Ca^{2+}$ and $K^+$ in cotton roots [28]. $Mg^{2+}$, as an essential nutrient, contributes to chlorophyll production. Hence, the reduced uptake of $Ca^{2+}$ and $Mg^{2+}$ due to soil salinity can negatively impact the growth and development of cotton plants [29]. Potassium is vital for cotton growth, nutrient distribution, and resistance to pests and diseases. In low-K soil, $Na^+$ can partially replace $K^+$ and promote plant growth due to their similar physical and chemical structure [30]. However, at higher concentrations of NaCl, the selectivity of potassium for cotton plants decreases significantly. When the $Na^+$ concentration surpasses a specific threshold, it competes with $K^+$ for transport and binding sites, resulting in a depletion of potassium [29]. In cotton leaves, potassium deficiency leads to a reduction in chlorophyll and photosynthesis, whereas an excessive absorption of $Cl^-$ inhibits the uptake of $NO_3^-$ and $H_2PO_4^-$ [31].

According to Brugnoli and Bjorkman (1992), the nitrogen content in cotton leaves decreases as the salt concentration increases [32]. Pessarkli and Tucker (1985) found that high salinity stress leads to a reduction in $^{15}N$ absorption, while low salinity has no significant impact on absorption [33]. When it comes to nitrogen uptake, NaCl stress has little effect on $NO_3^-$-N absorption but significantly inhibits the absorption of $NH^{4+}$-N. Using the $^{32}P$ labeling technique, Martinez and Läuchli (1991) discovered that salinity affects the absorption and transportation of phosphorus [34]. In cotton seedlings, under low phosphorus conditions, salt stress hinders the absorption of phosphorus, and moderate salinity reduces the transportation of $^{32}P$ from the cotton root to the shoot.

## 3. Strategies for Alleviating Salt Stress

High soil salinity adversely impacts cotton growth and yield, primarily due to osmotic stress, ion toxicity, and nutritional imbalances in saline soils. Thus, the reduction of salt content in the vadose zone and the creation of a conducive soil environment for cotton growth is the first strategy to combat salinity stress. The root zone soil environment is where salinity originates and subsequently causes stress. Any practice that improves even a portion of the root zone environment has the potential to mitigate salt damage. The second strategy involves enhancing salinity tolerance through chemical and biological methods.

### 3.1. Improvements of Root Zone Environment

Incorporating organic matter into the soil has been shown to enhance water-holding capacity and improve soil structure, thereby reducing salt accumulation [35]. Efficient irrigation practices, such as drip irrigation and sensor-based water application, have been found to minimize water loss through evaporation and leaching, thus preventing salt build-up [36]. Excess salts in the root zone can be leeched by applying water in excess of crop requirements, but proper drainage is essential to avoid waterlogging [37]. The application of specific soil amendments, such as gypsum or lime, can alleviate salinity stress by displacing sodium ions and balancing soil pH, respectively [37]. Crop rotation and intercropping with salt-tolerant species have been effective strategies in reducing salt accumulation in the root zone and mitigating salinity stress [38]. The use of organic or synthetic mulches on the soil surface can conserve soil moisture and reduce evaporation, thus preventing salt build-up [39]. Dong (2012) conducted two greenhouse experiments that showed that increased soil moisture and temperature can enhance seed emergence and seedling growth under salinity stress [40]. In the first experiment, cotton seeds were planted in pots with varying salinity levels (12%, 16%, and 18%) and water content using soils from the Yellow River Delta. Higher soil water content positively affected emergence and seedling growth at each salinity level, attributed to reduced osmotic stress and salt accumulation in leaves. The second experiment investigated the impact of soil temperature on cotton seeds planted in potted saline soils at different dates. Results indicated that soil temperatures between 20 °C and 30 °C benefitted seedling emergence and growth under salinity stress. These findings collectively demonstrate the effectiveness of improving the root zone environment by reducing salinity levels and increasing soil moisture and temperature in mitigating salinity stress in cotton.

### *3.2. Enhancing Cotton Salinity Tolerance*

#### 3.2.1. Unequal Salt Distribution in the Root Zone

A split-root experiment involved growing cotton plants with split roots in pots in a greenhouse, irrigating each root half with either the same or two different concentrations of NaCl [41]. The results demonstrated that when the entire root system was exposed to the same concentration of NaCl, there were significant reductions in plant growth, photosynthesis, and transpiration compared to the NaCl-free control. This also led to noticeable reductions in cotton seed yields. However, when only half of the root system was exposed to salt stress, the inhibitory effect of salinity was significantly reduced. Consequently, it was evident that non-uniform salinity in the root zone fosters improved cotton growth relative to uniform salinity.

Further research by Kong et al. [42] showed that under non-uniform salinity treatments, water use increased 2.1-fold in the 0/200 treatment (non-uniform salinity) and 1.4-fold in the 50/150 treatment compared to the 100/100 treatment (uniform salinity) control. Non-uniform salinity also led to reduced $Na^+$ content and increased $K^+$ content in leaves. $Na^+$ accumulation was observed in the "0" side roots of the 0/200 treatment, possibly due to the transportation of foliar $Na^+$ to roots through the phloem. Additionally, plants under non-uniform salinity exhibited higher $Na^+$ efflux from the root compared to those under uniform salinity. The efflux of $Na^+$ from the non- or low-salinity side was enhanced by the higher salinity side. However, the NaCl-induced $Na^+$ efflux and $H^+$ influx in roots were inhibited by amiloride and sodium orthovanadate. Overall, the non-uniform distribution of salt in the root zone increased the salinity tolerance of cotton plants.

#### 3.2.2. Chemical and Agronomical Enhancement

Improving cotton's salinity tolerance is a pivotal strategy to combat salinity stress. Agronomic measures, including seed priming, plant growth regulators (PGRs), and fertilizer application, offer practical and accessible means for enhancing cotton salinity tolerance and crop productivity.

Seed priming, a pre-sowing treatment, has emerged as a potential method to enhance the salinity tolerance of various crops, including cotton. Studies have shown that seed priming improves germination rates, seedling growth, and overall performance under salinity stress [43]. This process involves the controlled hydration and dehydration of seeds, triggering beneficial physiological changes that confer stress tolerance. Notably, osmopriming and hormonal priming have shown promising results in enhancing cotton's salt tolerance [44].

Plant growth regulators (PGRs) are chemical compounds that modulate plant physiological processes, including growth and development, and they play a crucial role in enhancing cotton's salinity tolerance [44,45]. Gibberellic acid (GA) and abscisic acid (ABA) have been extensively studied in cotton under saline conditions. GA application has been reported to alleviate the negative effects of salinity on cotton growth by promoting root elongation and nutrient uptake. Similarly, ABA treatment has been found to enhance water use efficiency and mitigate osmotic stress in cotton [45].

## 4. Agronomic Practices to Alleviate Salinity Stress

### *4.1. Plastic Mulching*

Cotton plants are particularly sensitive to salt stress during emergence and seedling stages, often leading to poor stand establishment and seedling growth in saline soils. As a successful stand establishment is vital for a high cotton yield, special attention should be given to emergence and stand establishment during field management.

Plastic mulching has emerged as a potential solution to mitigate salinity stress in cotton production (Figure 1). It involves covering the soil surface with plastic films, reducing direct contact between saline irrigation water and the plant root zone [46]. Plastic mulching enhances soil water retention, minimizes evaporation, and reduces saline water infiltration into the root zone. Moreover, plastic mulching leads to uneven salt distribution in the soil, allowing part of the root system to develop in relatively low-saline soil, effectively reducing salt damage [47].

**Figure 1.** Flat seeding under plastic mulching.

Several studies have demonstrated the positive impact of plastic mulching on cotton growth, yield, and fiber quality. Plastic mulching reduces salt stress-induced growth inhibition, improves plant height and biomass accumulation, and increases photosynthetic capacity [48]. Furthermore, plastic mulching promotes early flowering and boll formation, and enhances cotton fiber quality under salinity stress conditions [49]. Various mechanisms contribute to the positive effects of plastic mulching on cotton under salinity stress. Plastic mulching reduces soil evaporation, maintaining high soil moisture content and minimizing salt accumulation in the root zone. It also enhances nutrient uptake efficiency and improves ion homeostasis in cotton plants, reducing ion toxicity and imbalance [50]. Furthermore, plastic mulching promotes root growth, facilitating water and nutrient absorption.

Conventionally, row covering is applied after sowing. However, row mulching with plastic film can be performed 30 days before sowing (early mulching) to prevent salt accumulation and moisture loss in saline fields. Early mulching offers greater benefits in terms of stand establishment, plant growth, and yield. The superior advantages of early mulching are mainly due to better control of root zone soil salinity, elevated soil temperature, and reduced moisture loss [40]. Consequently, $Na^+$ accumulation in leaves and lipid peroxidation in cotton tissues decrease, and photosynthesis improves. Despite its higher cost, the increased yield resulting from mulching compensates for the additional expenses. Overall, early mulching presents itself as a promising measure in cotton cultivation in saline areas [51].

### *4.2. Furrow Seeding*

Due to evapotranspiration, leached salts tend to resurface in the soil [52]. Soil salinization is more pronounced when the water table is shallow and groundwater salinity is high. Dong et al. [41] investigated the impact of furrow-bed seeding in saline fields compared to flat beds and found that furrow-bed seeding resulted in unequal salt distribution, leading to significantly improved plant growth, yield, and earliness. This improvement was mainly attributed to reduced $Na^+$ accumulation, increased $K^+/Na^+$ ratio, improved transpiration, and enhanced photosynthesis, which serve as potential escape mechanisms against salinity stress [53].

In a study conducted by Dong et al. [53], it was found that combining plastic mulching with furrow seeding resulted in more significant improvements in stand establishment and yield compared to using either mulching or furrow seeding alone (Figure 2). These improvements were attributed to several factors. Firstly, the uneven distribution of salts in the soil was reduced, leading to reduced sodium ($Na^+$) uptake by both the roots and leaves of cotton plants. Secondly, the elevated soil temperature under the plastic mulch, combined with improved moisture availability in the root zone, facilitated better conditions for seed germination and seedling growth. Additionally, these conditions also contributed to a decrease in lipid peroxidation in cotton tissues, reducing cellular damage. Finally, enhanced photosynthesis was observed, which likely contributed to the improved overall growth and productivity of the cotton plants. Based on these findings, the integration of plastic mulching with furrow bed seeding appears to be a promising technique for cotton production in saline areas.

**Figure 2.** Furrow seeding under plastic mulching.

### 4.3. Delayed Planting

The delayed planting of cotton has been recognized as a management strategy to improve salinity tolerance in cotton plants. This approach allows growers to avoid planting during periods of higher soil salinity or low temperature, which can lead to considerable damage to the crop. Boquet et al. [54] highlighted the potential benefits of delayed planting for cotton grown in saline soils. They found that by delaying planting until soil salinity levels decreased, cotton plants showed improved growth, increased biomass, and higher yields compared to plants subjected to early planting. These positive outcomes reduced osmotic stress, as delayed planting allowed for better water uptake and reduced ion toxicity. In another study, Grieve et al. [55] evaluated the effects of delayed planting on the physiological responses of cotton plants under saline conditions. They observed that delaying planting reduced salt accumulation in the root zone and alleviated osmotic stress in cotton plants. The delayed plants exhibited better water relations, enhanced photosynthetic activity, and improved overall growth compared to those subjected to early planting. Furthermore, Shannon et al. [56] investigated the impact of delayed planting on fiber quality in cotton plants grown under saline conditions. They found that delayed planting led to improved fiber quality characteristics, such as increased fiber length, strength, and fineness. These improvements were attributed to reduced stress during fiber development, as delayed planting allowed the plants to establish healthier root systems and access less saline soil moisture.

Planting full-season cotton in saline fields of temperate areas typically leads to challenges, such as poor stand establishment, delayed maturity, and rising input costs [57]. However, Dong et al. [58] demonstrated that late planting of short-season cotton resulted in improved seed emergence and seedling growth due to elevated temperatures and reduced $Na^+$ concentration in cotton tissues compared to normal planting. Despite yielding comparable results to normal-planted full-season cotton, late-planted short-season cotton exhibited better earliness and required fewer inputs. Consequently, the net revenue from late-planting short-season cotton surpassed that of normal-planting full-season cotton. Thus, late planting of short-season cotton holds promise as a viable system for cultivating cotton in saline areas like the Yellow River Delta and similar ecologies [58].

### 4.4. Fertilizer Management

Implementing effective fertilizer and plant nutrition management strategies is pivotal in mitigating the adverse impacts of salinity on cotton crops while maintaining an optimal nutrient balance. Through strategic application, fertilizers can promote balanced nutrient uptake and counteract nutrient imbalances induced by salinity stress. Numerous studies have demonstrated that balanced fertilization with nitrogen (N), phosphorus (P), and potassium (K) improves cotton yield and quality under saline conditions [59,60]. Furthermore, the significance of micronutrients, such as boron (B) and zinc (Zn), has been identified in enhancing cotton's salt tolerance [61].

To ensure precise nutrient delivery while minimizing salt stress, fertigation techniques, including drip irrigation and controlled-release fertilizers, have been incorporated. These methods facilitate the efficient uptake of essential nutrients, thereby supporting cotton growth in saline environments [62,63]. Maintaining adequate levels of essential macronutrients, namely nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients, such as iron (Fe) and zinc (Zn), is vital for enhancing cotton's salinity tolerance [64,65]. Adequate nitrogen nutrition plays a crucial role in regulating osmotic potential and maintaining ion homeostasis, thereby reducing the toxic effects of salinity [59]. Phosphorus contributes significantly to energy transfer and carbon metabolism, thereby enhancing cotton's ability to cope with salinity stress. Additionally, potassium supplementation improves osmotic adjustment and enhances the activities of antioxidant enzymes. Furthermore, sulfur and calcium also contribute to cotton's salinity tolerance through various physiological mechanisms [66,67].

The implementation of organic amendments, such as compost and farmyard manure, has been proven to enhance soil structure, increase nutrient availability, and improve water retention capacity, ultimately promoting greater salinity tolerance in cotton plants. Additionally, the application of gypsum and amendments that are rich in calcium and magnesium can effectively minimize sodium uptake and enhance soil structure, thus facilitating improved salt tolerance in cotton [68].

In terms of nitrogen application, studies have shown that the early irrigation cycle application of nitrogen results in improved yield and fertilizer use efficiency [69]. Moreover, Keshavarz et al. [70] demonstrated that the application of potassium (K) promotes cotton growth and yield, particularly in saline soils. It has also been observed that high salinity levels have a significant detrimental effect on plant growth parameters, but this negative impact can be mitigated through foliar spray applications of $NH_4NO_3$ or KCl. Foliar nutrient spray has been proven to be beneficial for cotton growth and development under saline conditions [71]. Furthermore, research by Dong [40] suggests that a combination of both soil and foliar applications of $^{15}N$-labeled urea ($^{15}N$-4%, atom; 98.5% N; provided by the Institute of Chemical Industry, Shanghai, China) performs best in combating salinity stress, surpassing the effects of either application method when used separately.

### 4.5. Seed Priming

Seed priming is a pre-sowing technique that enhances seed performance and ultimately improves crop productivity under various environmentally stressful conditions. Salinity stress is a major challenge in cotton production, as it negatively affects its growth, development, and yield. However, seed priming has emerged as a promising approach to mitigate salinity stress and enhance cotton productivity.

One of the key methods of seed priming to alleviate salinity stress is osmopriming. Osmopriming involves the soaking of seeds in an osmotic solution containing compatible solutes such as polyethylene glycol (PEG) or KCl. These solutes act as osmoprotectants and facilitate the adjustment of seed moisture content, thereby promoting faster and uniform germination. Research has indicated that osmopriming significantly improves seed germination and seedling growth under saline conditions in cotton [72].

Another approach to seed priming for mitigating salinity stress involves the use of plant growth-promoting rhizobacteria (PGPR) as seed inoculants. PGPR effectively colonize plant roots and improve nutrient uptake, water retention, and hormonal regulation, leading to enhanced crop performance under salinity stress. For instance, a study by Hussain et al. [73] revealed that seed inoculation with PGPR strains such as Azospirillum and Azotobacter improved salt tolerance in cotton by enhancing root length, shoot height, and biomass production.

Furthermore, priming seeds with specific chemical compounds can also mitigate salinity stress in cotton. For example, priming seeds with antioxidants such as ascorbic acid (ASA) and α-tocopherol (TOC) has been found to alleviate the negative impact of salinity stress by reducing oxidative damage and maintaining cellular homeostasis. Adrees et al. [74] found that seed priming with ASA and TOC improved germination, seedling growth, and physiological attributes in cotton under saline conditions.

Conclusively, through the use of osmotic solutions, PGPR inoculants, and chemical compounds, seed priming has shown great potential in mitigating salinity stress and enhancing cotton productivity. These priming methods facilitate better germination, root development, nutrient uptake, and stress tolerance in cotton plants. Implementing seed priming techniques can thus contribute to sustainable cotton production in saline environments, ensuring better economic returns for farmers and meeting the global demand for cotton fiber.

### *4.6. Increase in Seeding Rate and Plant Density*

Increasing the seeding rate and plant density of cotton has been recognized as an effective strategy to enhance salinity tolerance in cotton plants. Ashraf and Ali [75] explored the impact of higher seeding rates on salinity tolerance in cotton plants. They found that increasing the seeding rate led to improved growth, biomass production, and yield in cotton plants under saline conditions. The researchers attributed these positive outcomes to a more optimal use of available resources, such as water and nutrients, as a result of increased plant density. Furthermore, Maas and Hoffman [76] investigated the effects of increased plant density on the salt tolerance of cotton. They observed that increasing plant density improved the competitive ability of cotton against salt stress, resulting in greater yields. Thus, higher plant densities allowed for the more efficient use of soil moisture and nutrients, which helped plants better withstand the negative effects of salinity. In another study, Munns et al. [18] explored the physiological responses of cotton plants to increased seeding rates under saline conditions. They found that higher seeding rates led to increased root biomass, enhanced water uptake capacity, and improved water-use efficiency. These physiological changes conferred a greater salinity tolerance to the cotton plants, as they were able to maintain better water status and cope with the osmotic stress imposed by high soil salinity.

High salinity adversely affects plant growth rate due to reduced water uptake and induces effects similar to those caused by water stress [17]. Excessive salt accumulation in the plant can lead to toxicity in older leaves, thereby decreasing the plant's photosynthetic capacity. Salinity-induced growth reduction may occur through altered water relations, hormonal imbalances, or disrupted carbon supply, with the significance of each process dependent on the response time scale [20]. Various studies have reported an increase in cotton yield under salinity stress with higher plant density [77,78]. This is attributed to the smaller plant size, which creates additional space between plant canopies, facilitating the growth of more plants [77]. Additionally, an increased plant population has been shown to promote earlier cotton maturation [79]. A recent field experiment by Dong et al. [42] demonstrated that under strong salinity conditions, higher plant density significantly improved seed cotton yield. Thus, it is recommended to consider increased plant density as a means of enhancing both yield and earliness in highly saline fields.

### *4.7. Utilization of Root-Associated Microorganism*

Microorganisms have been gaining attention for their role in mitigating salinity stress and improving cotton productivity. These beneficial microorganisms colonize the plant roots, enhancing nutrient uptake, water absorption, and hormonal regulation, thereby enabling plants to better cope with salinity stress. Utilizing microorganisms as bioinoculants can significantly improve cotton production under saline conditions. The arbuscular mycorrhizal fungi (AMF) have the ability to enhance P and Zn uptake and promote the accumulation of leaf proline [80]. However, it is important to note that the AMF species Glomus mosseae, isolated from saline soil, is less effective in alleviating salt stress compared to those from non-saline soil [81]. Micro-organisms with the PGPR effect, such as Pseudomonas fluorescens, produce the hormone IAA, which is involved in synthesizing important compounds during salinity stress [82]. Furthermore, PGPR colonization in the rhizosphere increases with moderate nitrogen application due to the role of nitric oxide (NO) as a signaling molecule in the denitrification process [83]. Additionally, melatonin, an indole hormone, can alleviate the negative effects of salt stress by reducing ROS production, mitigating ion toxicity, and increasing proline content in cotton seedlings [84].

One of the key ways to use microorganisms to mitigate salinity stress in cotton is through seed inoculation. Seed inoculation with PGPR strains, such as Bacillus, Pseudomonas, or Azospirillum, has been shown to improve salt tolerance in cotton plants. These bacteria establish a symbiotic relationship with the plant roots, stimulating root growth and enhancing nutrient acquisition. This ultimately leads to improved plant growth and better productivity in saline environments. Studies by Sarwar et al. [85] and Islam et al. [86] have demonstrated the positive effects of seed inoculation with PGPR on cotton growth and yield under saline conditions.

In addition to seed inoculation, microorganisms can also be applied to the field as soil amendments. The introduction of beneficial microorganisms into the soil promotes the development of a healthy rhizosphere, which positively impacts overall plant health. For instance, some PGPR strains have the capability to solubilize phosphorus, fix atmospheric nitrogen, or produce plant growth-promoting substances such as indole-3-acetic acid (IAA). These activities improve nutrient availability and hormone levels in the plant, enhancing its ability to withstand salinity stress. Research by Khan et al. [87] showed that the application of PGPR as a soil amendment significantly improved cotton growth, nutrient uptake, and yield under saline conditions.

Furthermore, the use of microorganisms in combination with other mitigation strategies, such as the application of organic amendments, can provide even greater benefits for cotton production under salinity stress. The joint action of microorganisms and organic amendments has been found to enhance cotton growth and yield under saline conditions, as depicted in studies by Shi et al. [88] and Nouman et al. [89]. Therefore, microorganisms, particularly plant growth-promoting rhizobacteria (PGPR) strains, offer a promising avenue to mitigate salinity stress and improve cotton productivity. Seed inoculation and soil amendment with selected beneficial microorganisms can enhance nutrient uptake, water absorption, and hormonal regulation, leading to improved plant growth and yield in saline environments. Integrating microorganisms into sustainable cotton production systems can contribute to the development of resilient agricultural practices that address the challenges of salinity stress.

### *4.8. Concave and Convex Cultivation*

The coastal saline soil, mainly in the Yellow River Delta, plays a crucial role as a prominent high-quality cotton production base in China. Nevertheless, challenges arise due to its high-water table, resulting in salt accumulation during spring and the consequent salinity-related damage to tillage soil, leading to poor seedling emergence and the breakage of cotton fields [31]. Moreover, cotton fields in this coastal region suffer from inadequate drainage, leading to frequent flooding after summer rains. This flooding, along with salinity stress, adversely affects the root system's inward growth in cotton plants, prompting a shift from aerobic to anaerobic respiration and hindering their growth and development. Consequently, cotton yield and fiber quality are compromised [90]. The cumulative impact of flooding and salinity stress leads to low yield and poor quality of cotton in heavily saline coastal lands.

Presently, prevailing methods of cotton cultivation in saline soils involve the extensive use of freshwater diffusion to reduce soil salinity before sowing cotton and other crops, requiring a considerable amount of water, typically exceeding 3000 $m^3$ per hectare. However, this approach is marred by the return of salts from deep soil to the surface during the period from pre-sowing irrigation to seeding, effectively diminishing the salinity reduction effect of pre-sowing irrigation. Furthermore, existing practices, such as ridge and furrow seeding, with or without plastic film mulching, aim to enhance cotton establishment but may lead to a period of bare soil exposure, hampering temperature regulation and moisture conservation. Additionally, planting cotton in furrows fails to mitigate crop flooding damage, particularly during the rainy season from July to August, leading to further yield losses or crop failure. Therefore, it is imperative to explore novel approaches for cultivating crops in saline soil that effectively address both salt and flooding stresses. To address this, a concave and convex cultivation method has been established to facilitate cotton seedling emergence in saline soil and alleviate crop flooding stress for stable and productive yields in these challenging environments (Figure 3).

**Figure 3.** Saline soil-grown cotton (before harvest) managed by convex and concave planting method.

Based on research and practice, the key points of "concave and convex" cultivation in heavy coastal saline land (0–20 cm soil salinity 0.5%–1.0%) can be summarized as follows.

Before winter, a ridge measuring 25–30 cm in height and 80 cm in width is established with a spacing of 160 cm between two ridges. Additionally, a ditch bed of 75 cm width is formed between the ridges. In winter, the ditch bed is irrigated with 100–200 $m^3$ of water to lower the salinity level to below 0.3%. By the end of February or early March the following year, a 90 cm wide plastic film is used to cover the ditch bed once the ground temperature stabilizes at 5 °C during 20–30 April. Using machinery, two rows of cotton or other crops are sown in the ditch bed, with row spacing set at 40–50 cm, thus completing the "concave" planting formation. The ditch bed, with the help of plastic film, maintains a low salinity level in the root zone soil, reducing salt damage and promoting seedling emergence and growth. In mid-June, crops at the squaring or adult stages exhibit greater salinity tolerance compared to the seedling stage. Consequently, the plastic film in the ditch bed is removed, and a ridge is formed along the cotton row, with a furrow created between two rows by piling soil up to the base of cotton plants before the rainy season (July to August). This transformation turns the ridge into a furrow and the ditch bed into a convex shape with machinery. During the rainy season, this facilitates proper drainage of the cotton fields to prevent flooding.

Overall, the "concave and convex" planting and cultivation method proves to be a simple and practical approach, aiding in the establishment of seedlings in saline land, effectively controlling floods with improved drainage, and significantly reducing yield loss [91].

The agronomic practices to alleviate salinity stress in cotton production summarized above are shown in Table 1.

**Table 1.** Agronomic practices to alleviate salinity stress.

| Agronomic Measures | Implementation Period | Effect | References |
|---|---|---|---|
| Plastic mulching | 30 days before sowing or after sowing | Enhances soil water retention<br>Minimizes evaporation<br>Reduces root zone salt accumulation | [40,46–51] |
| Furrow seeding | Sowing period | Unequal salt distribution in the root zone | [41,52,53] |
| Delayed planting | Sowing period | Promotes water absorption<br>Reduces ionic toxicity | [54–58] |
| Fertilizer management | Growth stage | Promotes balanced nutrient uptake; reduces toxicity<br>Enhances cotton salinity tolerance | [59–71] |
| Seed priming | Pre-sowing | Promotes seed germination and seedling growth<br>Improves stress resistance | [72–74] |
| Increase in seeding rate and plant density | Sowing period | Improves plant growth<br>Increases production<br>Promotes earlier cotton maturation | [42,75–79] |
| Utilization of root-associated microorganism | Seed inoculation used in field as soil amendments | Mitigates salinity stress<br>Improves cotton productivity | [85–89] |
| Concave and convex cultivation | Pre-sowing | Facilitates cotton seedling emergence<br>Improves drainage | |

## 5. Summary and Prospects

Over 800 million hectares of arable land are affected by salinity in the world. In China, saline–alkali soils account for 25% of farmland and are underutilized [92]. This statistic emphasizes the significant potential for cotton production in saline lands, subject to advancements in technology and research pertaining to cotton cultivation in such challenging soils. While the genetic breeding of cotton with improved salinity tolerance shows promise, practical agronomic practices that improve the root zone environment offer viable strategies to counteract the negative effects of salinity. Field management, such as furrow seeding, plastic mulching, densely planting, and appropriate fertilization, has the potential to substantially enhance cotton productivity in saline soils.

In order to advance knowledge in this field, future research endeavors on mitigating salinity stress and improving cotton productivity with agronomic practices should prioritize several aspects, as follows.

Firstly, a comprehensive understanding of the physiological and molecular mechanisms underlying salt tolerance in cotton plants is essential. This could be achieved by investigating the gene expression profiles, protein interactions, and regulatory networks involved in salt stress responses in cotton. Ashraf et al. [93] and Li et al. [94] provided valuable insights into the salt tolerance mechanisms in cotton, serving as a foundation for future investigations.

Secondly, exploring the role of soil amendments and nutrient management in alleviating salinity stress in cotton is crucial. Soil amendments, such as gypsum, organic matter, and zeolite, have been shown to improve soil structure and water-holding capacity, thus reducing the negative effects of salinity on cotton [95]. Additionally, optimizing nutrient management practices, including balanced fertilization, micronutrient supplementation, and efficient irrigation, can enhance cotton growth and yield under saline conditions [90].

Moreover, investigating the potential of using plant growth-promoting rhizobacteria (PGPR) for enhancing salt tolerance in cotton should be a priority. PGPR, such as Azospirillum and Pseudomonas, have been reported to stimulate plant growth, alleviate salt stress, and improve nutrient uptake in various crops [96]. Therefore, assessing the effectiveness of different PGPR strains on cotton salt tolerance could provide valuable insights into their application as biofertilizers in saline agricultural environments.

Furthermore, future research should focus on developing and implementing precision agriculture technologies for saline cotton fields. Remote sensing techniques, such as hyperspectral imaging and thermal imaging, can be used to detect early signs of salinity stress in cotton and facilitate targeted interventions [97]. Additionally, the integration of sensor-based irrigation systems and decision support tools can optimize water and nutrient management, tailoring them to the specific needs of cotton plants under salt stress conditions [98].

In conclusion, future research endeavors on mitigating salinity stress and improving cotton productivity with agronomic practices should prioritize understanding the physiological and molecular mechanisms of salt tolerance, exploring soil amendments and nutrient management strategies, investigating the efficacy of PGPR, and implementing precision agriculture technologies. These research areas hold the potential to significantly enhance cotton production in saline environments, ensuring sustainable and resilient cotton farming systems.

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