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DROUGHT STRESS MANAGEMENT FOR SUSTAINABLE COTTON PRODUCTION – A REVIEW

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ABSTRACT
Drought stress is one of the most important abiotic constraints affecting global cotton production due to its longer growth duration, higher water requirement, and sensitivity of fibre development processes to moisture deficits. Drought management is a major challenge for sustainable cotton production systems, due to the increased vulnerability of cotton-growing countries caused by increasing climate variability, irregular rainfall patterns, and declining freshwater availability. Even short-term water deficits can significantly reduce photosynthetic efficiency, disrupt physiological processes, and negatively affect fibre quality attributes, like length, strength, and fineness. Reduced leaf area, altered root architecture, stomatal regulation, and decreased carbon assimilation are examples of morphological and physiological responses to drought stress. The role of biochemical mechanisms such as osmotic adjustment, antioxidant defense systems, and hormonal signalling pathways is related to plant adaptation under water-limited conditions. Recent advances in breeding, such as Conventional breeding strategies, Marker-asissted selection, and CRISPR/Cas-based genome editing are evaluated for their potential to develop drought-tolerant cultivars while maintaining fibre quality traits. Agronomic strategies for drought mitigation and climate-smart drought management, such as precision agriculture, remote sensing, soil moisture monitoring, and crop simulation modelling, are innovative solutions for improving water-use efficiency and supporting decision-making under changing climate conditions. Overall, integrated drought management strategies are essential for safeguarding yield stability, maintaining premium fibre quality, and ensuring the long-term viability of cotton under increasing drought stress.

KEYWORDS: Cotton, drought stress, climate-smart agriculture

BACKGROUND
Cotton (*Gossypium* spp.) is one of the most important natural fibre crops in the world, serving as a cornerstone of the textile and apparel industry (Tausif et al. 2018) and supporting the livelihoods of millions of farmers worldwide. It contributes significantly to national economy through employment generation, industrial development, and export earnings, particularly in developing countries (OECD/FAO, 2023). Despite its economic importance, cotton cultivation is increasingly threatened by abiotic stresses, with drought stress emerging as the most common and yield-limiting factor (Mahmood et al. 2022). Climate change has made water scarcity worse by altered rainfall patterns, increased evapotranspiration, and a higher frequency of extreme weather events especially in arid and semi-arid cotton growing regions (Lesk et al. 2016).
Cotton is susceptible to drought stress due to its longer growing season and higher physiological water demand during critical developmental stages such as square initiation, flowering, and boll formation (Ul-Allah et al. 2021). Water deficits during these stages can often lead to decreased photosynthetic efficiency, impaired nutrient uptake, increased oxidative damage, and hormonal imbalances, resulting in excessive square and boll shedding and reduced boll weight (Basu et al. 2016). There is growing recognition that drought tolerance in cotton is a multifaceted trait requiring an integrated management approach (Khan et al. 2018). This should be an integrated strategy that incorporates effective water management, soil moisture retention, physiological processes, breeding and biotechnological solutions to produce drought resistant cultivars. Climate-smart technologies like precision irrigation, remote sensing, and decision-support systems provide the opportunities to optimize the efficiency of water usage and reduce the risk of drought on the field level (Xing and Wa.ng, 2024).

1. Impact of drought stress on growth, yield and fibre quality of Cotton
Cotton has relatively higher water requirements throughout its growth cycle, with critical sensitivity during its reproductive stages (Zonta et al. 2017). Adequate soil moisture is essential during square initiation, flowering, and boll development for maintaining photosynthesis, assimilate partitioning, boll retention and fibre elongation (Pettigrew, 2004). Drought stress during germination and seedling establishment reduces seed imbibition, delays emergence, and weakens early root and shoot development, leading to poor crop stand establishment. During early vegetative stages, it often restricts leaf area expansion and root development (Pace et al. 1999), nutrient uptake (Fahad et al. 2017), and photosynthetic activity, thereby limiting plant growth and biomass accumulation. However, the most severe effects of drought in cotton occur during the flowering and boll development stage (Snowden et al. 2014), where disruption of hormonal balance, particularly abscisic acid and ethylene signalling,

leads to increased shedding of squares and bolls (Tariq et al. 2017) and reduced boll retention (Guinn et al. 1981). Drought stress during boll development further decreases boll weight (Zou et al. 2022) and assimilate supply (Gao et al. 2020). Prolonged drought stress reduces nutrient uptake and photosynthetic efficiency, further limiting boll growth and fibre maturation.

2. Physiological and Biochemical Mechanisms of Drought Tolerance in Cotton

Drought tolerance in cotton is governed by a complex network of physiological, biochemical, and hormonal mechanisms that determine the plant's ability to maintain growth, yield, and fibre quality under water-limited conditions (Tardieu et al. 2018; Manju et al. 2025) (Table 1). Drought tolerance in cotton involves active regulation of water relations, cellular protection, and metabolic stability (Ullah et al. 2017) (Fig.1).

2.1. Water-Use Efficiency (WUE)

WUE in cotton is achieved through optimized stomatal regulation, reduced transpiration losses, and improved carbon assimilation efficiency (Leakey et al. 2019). Under drought conditions, partial stomatal closure helps in water conservation by reducing transpiration, but excessive closure of stomata can severely limit CO_2 uptake and photosynthesis (Matkowski and Daszkowska-Golec, 2023). Drought-tolerant cotton genotypes have a balanced stomatal response that reduces water loss and maintain sufficient photosynthetic activity (Vijayalakshmi et al. 2026). Enhanced root-to-shoot signalling, hydraulic conductivity, and efficient assimilate partitioning helps to increase WUE during drought stress (Nan et al. 2026).

2.2. Osmotic Adjustment

Osmotic adjustment is an important drought tolerance mechanism that enable cotton plants to maintain cell turgor and metabolic activity in low water potential conditions. This process involves the accumulation of compatible solutes, or osmolytes, such as proline, glycine betaine, soluble sugars, and organic acids (Ozturuk et al. 2021). Proline accumulation is one of the most reported osmotic responses in cotton under drought stress (Sarwar et al. 2025). Proline functions not only as an osmolyte but also as a stabilizer of proteins and membranes and a scavenger of reactive oxygen species (ROS) (Liang et al. 2013). Similarly, soluble sugars such as sucrose and fructose help in maintaining osmotic balance and they are used as carbon sources for fibre development (Parida et al. 2007).

2.3. Antioxidant Defense System

The excessive production of reactive oxygen species, including superoxide radicals, hydrogen peroxide, and hydroxyl radicals, which can cause oxidative damage to cellular components due to drought stress (Zafar et al. 2023). Cotton crop activates a complex antioxidant defense mechanism including of enzymatic and non-enzymatic antioxidants to mitigate the oxidative stress. Key enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which work sequentially to detoxify ROS (Feller and Vaseva, 2014). Non-enzymatic antioxidants such as ascorbate, glutathione, carotenoids, and phenolic compounds increase the cellular protection (Calvo et al. 2014). Drought-tolerant genotypes have higher antioxidant enzyme activity and improved redox homeostasis, which helps in maintaining membrane integrity and metabolic processes during stress in cotton (Khan et al. 2026). Failure of maintaining antioxidant balance under prolonged drought leads to lipid peroxidation, chlorophyll degradation, and premature senescence, which further results in reducing yield and fibre quality (Rehman et al. 2022).

2.4. Hormonal Regulation under Drought

Plant hormones play a key role in coordinating the drought stress responses through growth regulation, development, and stress signalling pathways. Abscisic acid (ABA) is the primary hormone involved in drought response, which regulates stomatal closure, root growth, and stress-responsive gene expression (Trivedi et al. 2016). Elevated ABA levels promote water conservation but also inhibit cell elongation and reproductive development if excessively accumulated during drought stress. In cotton, hormonal cross-talk between ABA, auxins, cytokinins, and ethylene determines the balance between the stress tolerance and growth maintenance (Jogawat et al. 2021). Reduced cytokinin levels under drought are associated with leaf senescence and increased ethylene production promotes boll shedding.

Table 1. Physiological and Biochemical Mechanisms of Drought Tolerance in Cotton

Mechanism	Key components	Functional role	References
Water-use efficiency	Stomatal regulation, transpiration control	Reduced water loss with sustained photosynthesis	(Leakey et al. 2019; Matkowski and Daszkowska-Golec, 2023; Vijayalakshmi et al. 2026; Nan et al. 2026)
Osmotic adjustment	Proline, sugars, glycine betaine	Maintenance of cell turgor	(Ozturuk et al. 2021; Sarwar et al. 2025; Liang et al. 2013; Parida et al. 2007)
Antioxidant defense system	SOD, CAT, POD, ascorbate	Protection against oxidative stress	(Zafar et al. 2023; Feller a.nd Vaseva, 2014; Calvo et al. 2014; Khan et al. 2026; Rehman et al. 2022)

Hormonal regulation	ABA, auxins, cytokinins	Stress signaling and growth balance	(Trivedi et al. 2016; Jogawat et al. 2021)

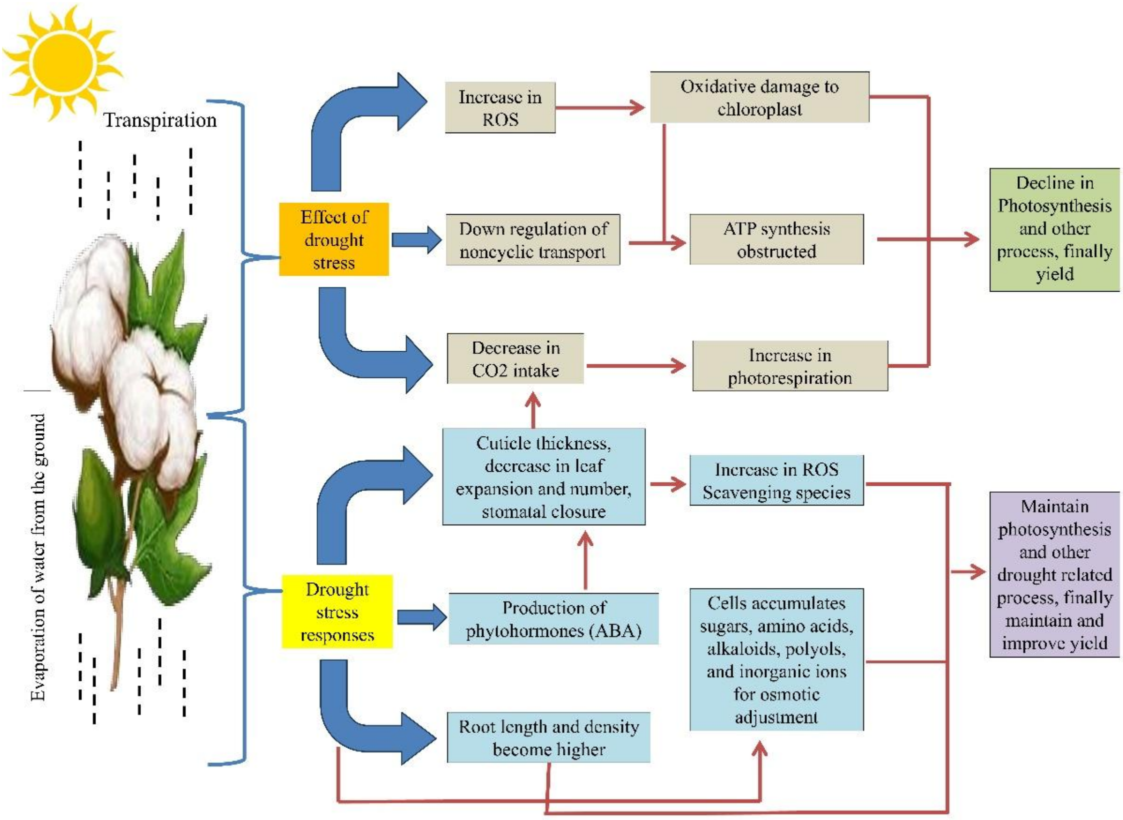

Fig.1 Effects of drought stress and their responses in cotton crop

3. Advances in breeding, biotechnological, and molecular approaches for Drought-Tolerant Cotton

Breeding for drought tolerance in cotton is particularly challenging due to the crop's narrow genetic base and the complex, polygenic nature of drought tolerance traits (Guo et al. 2022). Moreover, breeding efforts must balance stress tolerance with the maintenance of superior fibre quality, which defines the economic value of cotton (Witt et al. 2018). To overcome these limitations, biotechnological and molecular approaches offer powerful strategies for improving drought tolerance in cotton by enabling precise manipulation of genes and regulatory pathways involved in stress adaptation (Ghorbanzadeh et al. 2025), thereby reducing the time required for cultivar development and minimizing potential trade-offs between stress resilience and fibre quality (Rajan et al. 2025).

3.1. Conventional Breeding Strategies

Conventional breeding approaches rely on phenotypic selection for drought-adaptive traits such as deeper root systems, improved water-use efficiency, and reduced boll shedding under drought stress conditions (Guo et al. 2024). Pedigree breeding, backcrossing, and recurrent selection are widely used for conventional methods to develop drought-tolerant cotton cultivars, as they enable systematic evaluation of segregating lines across the generations under both stress and non-stress conditions (Gebremedhin, 2021). Mass selection and pure-line selection are also applied to enhance the yield ability and drought resistance, particularly when screening the parental lines with contrasting tolerance profiles (Ranjith & Srinivasa Rao, 2021). Selection for drought tolerance in cotton is constrained by strong genotype × environment interactions and the difficulty of reliably screening large populations under controlled drought conditions (Gören and Tan, 2024). Significant genotype × treatment interactions for most traits have been detected in cotton drought studies, indicating that the genotypes respond variably across stress environments and that control treatments are essential when evaluating drought tolerance (Sun et al. 2023).

3.2. Marker-Assisted Selection

Marker-assisted selection (MAS) offers a more precise approach for improving drought tolerance by enabling the identification and introgression of quantitative trait loci (QTLs) associated with stress-adaptive traits (Ashraf et al. 2008; Ashraf et al. 2010). Several QTLs related to water-use efficiency, osmotic adjustment, and antioxidant activity have been identified in cotton (Saranga et al. 2004). Furthermore, the QTL collections and markers that have been established can help to identify new applicant genes associated with drought tolerance. The list of different QTL traits linked to drought tolerance is provided below (Table 2). Especially to mitigate the effects of drought stress in cotton, molecular markers such as HY5-specific CAPS, PHYA, PHYB, and dCAPS have been developed for MAS (Bibi et al. 2024; Kushanov et al. 2016).

3.3. Genomic and Transcriptomic Approaches

Advances in genomics and transcriptomics have facilitated the identification of drought-responsive genes and regulatory networks in cotton (Bano et al. 2022). High-throughput sequencing technologies have revealed key genes involved in ABA signaling, osmolyte biosynthesis, antioxidant defense, and stress-induced transcriptional regulation (Hasan et al. 2019). Genome-wide association studies further revealed four candidate genes like *RD2*, *HAT22*, *PIP2*, and *PP2C*—as potentially important for drought tolerance in upland cotton (Hou et al. 2018). Comparative transcriptomic analyses across cotton diploids identified 287 genes exhibiting conserved regulatory responses to drought, including 16 transcription factors that serve as central regulators of stress response mechanisms (Huan et al. 2025). The ABA signaling pathway involves key receptors like *GhPYL9-11A* (Liang et al. 2017), which is highly induced by drought and activates downstream stress responses, while *GhWRKY21* regulates ABA-mediated drought tolerance by facilitating *GhHAB* expression (Wang et al. 2021). For osmolyte biosynthesis, transcriptomic and metabolomic analyses revealed that drought stress induces phenylpropane pathway genes (*PAL*, *C4H*, and *4CL*) involved in lignin and flavonoid synthesis, enhancing drought resistance (Sun et al. 2025). Antioxidant defense mechanisms depend on major enzymes, such as ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and glutathione reductase (GR), which are crucial for the cotton crop response to environmental stresses (Sheri et al. 2023).

3.4. Genetic Engineering for Drought Tolerance

Genetic engineering has been widely explored to improve drought tolerance in cotton through overexpression of stress-responsive genes (Ahmed et al. 2024). These include genes that encodes osmoprotectants, transcription factors, antioxidant enzymes, and signalling proteins that are involved in ABA-mediated stress responses (Saud and Wang, 2022). Transgenic approaches that target osmotic adjustment and antioxidant defense pathways have shown potential to maintain fibre elongation and boll development during drought stress in cotton (Qamer et al. 2021).

3.5. CRISPR/Cas-Based Genome Editing

CRISPR/Cas-based genome editing represents a transformative technology for crop improvement due to its precision, efficiency, and potential for transgene-free modifications (Nerkar et al. 2022). Several studies have recently started attempting to use CRISPR/Cas9 for direct "Point-to-point" gene editing in stress response genes (Luqman et al. 2025). CRISPR/Cas systems have been successfully used to edit genes associated with stress signalling, hormone metabolism, and transcriptional regulation in cotton (Kumar et al. 2024). Recent advances have shown that CRISPR/Cas9 can successfully edit *GhDREB2* and other stress-related genes to improve drought tolerance in cotton, with phenotypic and transcriptomic validation confirming the enhanced resistance (Huang, 2025). Novel delivery methods, like cotton leaf crumble virus (CLCrV)-mediated CRISPR systems, have enabled efficient adenine base editing with high specificity in cotton, that providing powerful tools for editing multiple target genes simultaneously (Zhang et al. 2026). Various CRISPR/Cas systems including Cas9, nCas9, and Cas12a have been employed to edit cotton genes associated not only with abiotic stress tolerance but also with fibre quality, flowering time, root architecture, and seed oil content (Saleem et al. 2024).

3.6. Omics-Based Strategies

Advanced omics-based biotechnologies, enabling the collection of omics data like transcriptomics, genomics, metabolomics, and proteomics that have improved the knowledge of cotton crop responding to drought stress (Sharif et al. 2024). Proteomic analysis between the drought-tolerant cotton cultivar KK1543 and drought-sensitive cultivar Xinluzao26 has shown that, difference in expression of proteins is associated with energy metabolism, antioxidant defense, transport and stress-responsive pathways (Zhang et al. 2016). Drought tolerance in cotton is involved with coordinated regulation of gene expression and metabolite accumulation especially in flavonoid and phenylpropanoid biosynthesis pathways and found key hub genes involving in drought adaptation through integrated transcriptomic and metabolomic analyses (Han et al. 2025). Metabolomic studies demonstrated that biosynthetic pathways of kynurenine and polyamine, along with glycerophospholipid metabolism, plays a crucial role in cotton drought tolerance by reactive oxygen species scavenging and reconstructing cell membranes (Zhang et al. 2021). Integrated multi-omics datasets through systems biology framework helps to identify key regulatory hubs and guide targeted interventions for improving drought tolerance in cotton (Khan et al. 2023).

4. Agronomic Strategies for Drought Management

Agronomic interventions are the most practical and cost-effective strategies for minimizing drought stress in cotton. These strategies aim to optimize water availability, reduce soil moisture loss and improve plant resilience in water-deficit situations (Table 2).

4.1. Irrigation Management

Deficit irrigation increases water productivity without reducing yield, when sprayed below the full crop evapotranspiration requirements during non-critical growth stages (Fereres and Soriano, 2007). Micro-irrigation systems like drip irrigation lowers the evaporation losses and increases efficiency by precisely delivering water to the root zone (Camp, 1998). Subsurface drip irrigation reduces surface evaporation and improves water distribution (Deshpande et al. 2024). Sprinkler systems, like center pivot and lateral move designs, provide uniform application and are useful on uneven topography and sandy soils (Oliver et al.2013). Modern low-pressure, automated nozzles lower wind drift and evaporation losses, further increasing efficiency (Evans and Sadler, 2008). Fine droplets from jet, mist and spray systems reduces plant temperature, maintain favourable canopy conditions and lessen drought stress (Pereira et al. 2002). Bubbler irrigation applies low-pressure water directly to the soil near the plant base (Rashad, 2013), it minimises runoff and deep percolation losses (Alurbaye et al. 2020) and is ideal for row crops like cotton in arid dry regions (Burt and Styles, 2007). These irrigation systems when combined with sensor-based scheduling and climate-smart technologies to enhance their efficiency. Overall, modern irrigation methods combined with precise scheduling ensures optimal soil moisture, improve water productivity, and maintain yield and fibre quality in cotton during drought conditions (Wang et al. 2024).

4.2. Soil Moisture Conservation Practices

Soil moisture Conservation practices are vital for sustaining crop production under drought. They help to retain water, lower evaporation losses, and improves soil health. Mulching with organic or synthetic materials reduce evaporation, moderates soil temperature, and boosts water storage, infiltration, and cotton yield in water-limited areas by cutting down surface runoff (Shirol et al. 201; Iqbal et al. 2021). Conservation tillage practices like minimum tillage and zero tillage preserves soil structure, builds organic matter, and improves soil aggregation which helps in increasing water-holding capacity. Conservation tillage improves soil moisture retention and water-use efficiency in cotton-based systems, particularly in arid and semi-arid regions (Lal, 2015; Hobbs et al. 2008). Residue retention protects soil surface from sunlight and wind, which reduces evaporation losses and improves microclimatic conditions around the root zone. Cover cropping and organic amendments (farmyard manure, compost) improves soil organic carbon and porosity, reduce soil erosion and enhance infiltration and moisture storage, sustaining crop growth during fallow periods and drought stress (Blanco-Canqui et al. 2015). These practices improve water productivity and climate resilience in cotton production when combined with effective irrigation.

4.3. Crop Geometry and Plant Population

Crop geometry and plant population affects the light interception, root distribution, and soil moisture use. Optimal plant spacing lowers the competition for water, nutrients, and light which ensure the efficient usage of resources. Research have shown that wider spacing during drought conditions promote deeper root growth and better soil moisture extraction, improving the plant survival and productivity (Bednarz et al. 2000). Maintaining the plant population is necessary for balancing vegetative and reproductive growth under drought stress. High density planting boosts competition for scarce soil moisture, which further reduces boll formation and fibre quality. Moderate plant density improves canopy structure, aeration, and water-use efficiency, under drought stress. Row spacing and planting patterns affect the microclimate within the crop canopy. Narrow row spacing can improve ground cover and reduce soil evaporation, whereas wider spacing can ease the competition for water during severe drought. Adjusting crop geometry based on the soil type, rainfall patterns, and irrigation availability is important for maximising yield and maintaining fibre quality in the cotton systems (Ritchie et al. 2007; Yang et al. 2014).

4.4. Nutrient Management under Drought

Nutrient management for improving drought tolerance in cotton is based on supporting osmotic regulation, enzyme activation, and maintaining cellular integrity. Nutrient uptake is restricted due to its low soil moisture and impaired root activity (Hussain et al. 2018). Nitrogen management requires careful optimization, as both the excess and deficiency can affect the plant growth (Sulaman et al. 2025). Under low-moisture condition, controlled and nitrogen split application enhances its nutrient uptake efficiency and minimises losses (Iqbal et al. 2020). Balanced nitrogen supply promotes leaf area development, chlorophyll content, photosynthesis, and biomass accumulation under drought stress (Bondada and Oosterhuis, 2001; Gerik et al. 1996). Phosphorus is important for root development and transfer of energy, by enabling water extraction from deep soil layers (Iqbal et al. 2023). Potassium plays a major role by controlling stomatal movement, maintaining cell turgor, and improving water-use efficiency (Akhtar et al. 2023). Adequate potassium fertilization enhances photosynthetic efficiency and reduces oxidative damage (Cakmak, 2005; Pettigrew, 2008). Micronutrients and foliar nutrition improve drought tolerance by boosting metabolic and antioxidant activities (Ahanger et al. 2016; Khattak et al. 2022). Elements like zinc (Zn) and boron (B) are involved in enzyme activation, membrane stability, and reproductive development are often deficient during drought stress (Arinaitwe et al. 2026; Wu et al. 2015). Foliar application of nutrients overcome soil-related constraints and ensures rapid nutrient availability during the critical growth stages like flowering and boll formation (Waraich et al. 2011; Dordas, 2008).

Table 2. Agronomic Strategies for Drought Management in Cotton

Strategy	Key practice	Expected outcome	References
Irrigation management	Deficit irrigation, drip irrigation, Sub surface drip irrigation (SDI), Sprinkler irrigation, Bubble irrigation, Jet, mist and spray systems, Sensor based scheduling.	Improved water productivity, Reduced evaporation loss, Enhanced yield and fibre quality.	(Fereres and Soriano, 2007; Camp, 1998; Deshpande et al. 2024; Oliver et al. 2013; Evans and Sadler, 2008; Pereira et al. 2002; Rashad, 2013; Alurbaye et al. 2020; Burt and Styles, 2007; FAO, 2022)

Soil conservation	Mulching, conservation tillage, residue retention, cover cropping, organic amendments.	Increased soil moisture retention, reduced evaporation, improved soil structure and microbial activity.	(Shirol et al. 2021; Iqbal et al. 2021; Lal, 2015; Hobbs et al. 2008; Blanco-Canqui et al. 2015)
Crop geometry	Optimum spacing, row arrangement, moderate plant density, canopy management.	Reduced competition for water, improved root development, better light interception and WUE.	(Bednarz et al. 2000; Ritchie et al. 2007; Yang et al. 2014)
Nutrient management	Balanced fertilization (N, P, K), split nitrogen application, potassium supplementation, micronutrients (Zn, B), foliar application.	Enhanced osmotic regulation, improved photosynthesis, reduced oxidative stress, better drought tolerance.	(Hussain et al. 2018; Sulaman et al. 2025; Iqbal et al. 2020; Bondada and Oosterhuis, 2001; Gerik et al. 1996; Iqbal et al. 2023; Akhtar et al. 2023; Cakmak, 2005; Pettigrew, 2008; Ahanger et al. 2016; Khattak et al. 2022; Arinaitwe et al. 2026; Wu et al. 2015; Waraich et al. 2011; Dordas, 2008)

5. Role of Plant Growth Regulators and Biostimulants in Drought Mitigation

Drought tolerance in cotton is enhanced by plant growth regulators (PGRs) and biostimulants through physiological processes, hormonal balance, and stress-responsive pathways (Raza et al. 2024).

5.1. Growth Regulators in Drought Mitigation

Salicylic acid is one of the plant growth regulators, which is widely reported to improve drought tolerance by improving photosynthetic efficiency, antioxidant enzyme activity, and osmotic balance (Gonzalez–Villagra et al. 2022). Exogenous application of salicylic acid in cotton under drought stress is found to reduce oxidative damage, stabilize chlorophyll content, and improve boll retention (Noreen et al. 2013). Salicylic acid interacts with abscisic acid signalling, by helping to regulate stomatal conductance without severely affecting carbon assimilation (Saleem et al. 2020). Jasmonic acid plays a vital role in stress signalling and defense responses (Wang et al. 2021). Jasmonic acid drives adaptive responses like enhanced root growth and antioxidant activity during drought stress (Riemann et al. 2015). Excess accumulation of jasmonic acid suppresses plant growth, so that precise application timing and concentration are necessary (Shahzad et al. 2026). Brassinosteroids improves drought tolerance by enhancing cell membrane stability, photosynthetic performance, and antioxidant defense (Farooq et al. 2009).

5.2. Biostimulants and Natural Extracts

Biostimulants, comprising of seaweed extracts, humic substances, and amino acid formulations, are important for their ability to enhance drought tolerance through various physiological processes (Ma et al. 2022; Garcia–Caparros et al. 2025). Bioactive compounds in seaweed extracts such as polysaccharides, betaines, and phytohormone- like substances helps to improve water-use efficiency and stress resilience (Santaniello et al. 2017). Foliar application of seaweed extracts has been associated with increased leaf water status, reduced oxidative stress, and enhanced fibre quality under drought stress in cotton (Hassan et al. 2025). Humic substances improve soil structure, water-holding capacity, and nutrient availability, indirectly supporting drought tolerance (Khan et al. 2017). Amino acid-based biostimulants lead to osmotic adjustment and act as precursors for stress-related metabolites (Nephali et al. 2021). These products are particularly useful in mitigating short-term drought stress and enhancing recovery following irrigation (Van Oosten et al. 2017).

5.3. Microbial Inoculants

Beneficial soil microorganisms, especially plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), play an important role in improving drought tolerance in cotton (Ren et al. 2026; Mikiciuk et al. 2024). PGPR enhances root growth, nutrient uptake, and hormonal balance (Vacheron et al. 2013). AMF improves soil moisture absorption through extensive hyphal networks (Affortit et al. 2023). In cotton, microbial inoculation has been shown to enhance water-use efficiency, reduce stress-induced ethylene production, and improve yield stability under drought conditions (Sabagh et al. 2022; Ren et al. 2025). Integrating microbial inoculants into drought management strategies offer a sustainable and eco-friendly approach towards improving resilience.

6. Climate-Smart Drought Management Strategies

Climate-smart agriculture integrates technological innovations with sustainable management practices to enhance the crop resilience under changing climatic conditions (Safdar et al. 2024). Climate-smart strategies aim to optimize water use, reduce drought risk, and improve decision-making at the farm level in cotton systems (Bayramova et al. 2024).

6.1. Precision Agriculture Tools

Precision agriculture tools play a vital role in climate-smart drought management by enabling site-specific and real-time monitoring of crop and soil conditions in cotton systems (Gürsoy 2024). Remote sensing technologies, such as satellite imagery and unmanned aerial vehicles (UAVs), are used to assess crop water status through vegetation indices (Lacerda et al. 2022). These tools help to detect early drought stress by identifying variations in the crop canopy temperature and chlorophyll content before the occurrence of visible symptoms (Mulla, 2013). Soil moisture sensing technologies, like time-domain reflectometry (TDR), capacitance probes, and tensiometers provide accurate measurement of soil water availability at different depths, facilitating precision irrigation scheduling based on actual crop water requirement. Research show that sensor-based irrigation management improves water-use efficiency and reduces water losses when comparing with conventional irrigation practices (Evett et al. 2012; O'Shaughnessy et al. 2023). Variable rate technology (VRT), integrated with global positioning system (GPS) and geographic information system (GIS), enabling different application of water and nutrients across the field, optimizing input use under spatial variability and enhancing drought resilience (Gebbers and Adamchuk, 2010). These systems integrate sensor data, weather forecasts, and crop models to automate the irrigation scheduling and improve decision-making under drought stress conditions (Vellidis et al. 2008; Wolfert et al. 2017). Precision agriculture tools contribute to improved yield stability, enhanced water productivity, and sustained fibre quality in cotton through increasing climate variability by enabling proactive and precise resource management.

6.2. Modelling and Forecasting

Modelling and forecasting tools are crucial for climate-smart drought management in cotton, as they enable quantitative prediction of crop growth, yield, and water requirements during variable environmental conditions. Process-based crop simulation models such as DSSAT and AquaCrop integrate climatic variables, soil moisture dynamics, and crop physiological processes to simulate cotton growth under water-limited conditions (Hoogenboom et al. 2019; Steduto et al. 2012). These models are useful in identifying the sensitive phenological stages and optimizing irrigation strategies to minimise drought-induced yield loss (Sindarov et al. 2025). Drought forecasting approaches utilize long-term climatic datasets, seasonal forecasts, and atmospheric models to predict the onset, duration, and severity of drought events (Hao et al. 2018). Advances in climate modelling, such as the use of coupled ocean–atmosphere models, have improved the reliability of seasonal drought predictions in agricultural systems (Mishra and Singh, 2010). These forecasts allow farmers and researchers to implement anticipatory measures such as altering planting windows, selecting drought-resilient genotypes, and planning supplemental irrigation well in advance of stress occurrence. The integration of modelling tools with decision support systems (DSS) and geospatial technologies enhances the adaptive farm management under climate variability (Ale et al. 2023). DSS platforms combine model outputs with real-time field data and remote sensing inputs to simulate multiple management scenarios and recommend optimal practices (Jones et al. 2017). In cotton-based systems, these integrated approaches improve water productivity and reduce climate risk by enabling dynamic adjustment of irrigation and nutrient management strategies, by strengthening the overall resilience of cotton production systems (Mubeen et al. 2020).

6.3. Integrated Crop Management Systems

Integrated crop management (ICM) systems provide a holistic approach to drought mitigation in cotton by combining improved varieties, agronomic practices, and resource management strategies into a united framework. The integration of drought-tolerant cultivars with optimized agronomic practices such as appropriate sowing time, plant spacing, and crop rotation improves system resilience under water-limited conditions. Studies shows that combining genetic improvement with agronomic optimization significantly improves the water-use efficiency and yield stability in cotton-based systems (Hatfield and Dold, 2019). A major component of ICM is integrating of soil and water conservation practices to enhance moisture availability and sustain crop growth during drought periods. Practices such as conservation tillage, residue mulching, and cover cropping improve soil organic matter, increase water infiltration, and reduce evaporation losses (Lal, 2015). These approaches also promote better root development and soil microbial activity, which are essential for improving the nutrient uptake and maintaining the physiological stability in cotton during drought stress conditions.

ICM systems emphasize the synchronization of nutrient management, biological inputs, and crop protection measures that optimize the overall crop performance. Balanced fertilization, especially adequate supply of potassium, supports stomatal regulation and osmotic balance, while the use of beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) enhances root growth and stress tolerance (Vessey, 2003). The integration of these various components, creates synergistic effects that improve drought resilience, maintain fibre quality, and ensure sustainable productivity in cotton under changing climatic conditions.

Future Prospects

Future studies should concentrate on creating cotton cultivars that are resistant to climate change using combined breeding, molecular, and biotechnological techniques. To close the gap between lab results and on-farm implementation, more focus must be placed on multi-environment field trials, participatory breeding, and translational research. Predicting the effects of drought and optimising water management are made possible by the combination of machine learning and artificial intelligence with precision agricultural techniques. The long-term sustainability of cotton production in the face of growing climate uncertainty will depend on interdisciplinary cooperation and sustainable water management practices.

CONCLUSION

Drought stress is a major threat to cotton productivity and fibre quality, worsened by climate change and water scarcity. Sensitivity of cotton to drought during critical growth stages requires integrated management strategies that include physiological, biochemical, genetic, agronomic, and technological approaches. Cotton crop are able to withstand drought stress and maintain growth, yield, and fibre quality through physiological and biochemical processes, such as enhanced water-use efficiency, osmotic adjustment, antioxidant defense, and hormonal regulation. Advances in understanding the drought tolerance mechanisms such as marker-assisted selection, genetic engineering, CRISPR/Cas-based genome editing and multi-omics analyses provides a foundation for breeding and biotechnological innovations. Agronomic practices like optimized irrigation, soil moisture conservation, nutrient management, and crop geometry adjustments provide practical, and cost-effective solutions for immediate drought mitigation. Complementary use of plant growth regulators, biostimulants, and microbial inoculants further enhances drought resilience. Climate-smart strategies utilizing precision agriculture, modelling, and integrated crop management allows dynamic, data driven decision-making to optimize the water use and sustain yield and fibre quality under variable environmental conditions. Overall, a multidisciplinary, coordinated approach is necessary to protect sustainable cotton production in increasingly water-limited and climate-stressed environments.

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