

Research Insight

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Climate-Smart Cotton Farming: Adapting Field Practices to Drought and Heat Stress

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Abstract With the increasingly severe global climate change, drought and high-temperature stress have become the main environmental factors restricting the improvement of cotton yield and quality. The traditional field management model has many limitations in responding to extreme climate events, making it particularly urgent to promote the application of climate-smart agriculture in cotton production. This study focuses on the physiological response mechanisms of cotton under drought and high-temperature stress conditions. It systematically sorts out the key technical paths such as current climate-intelligent farming measures, breeding of stress-resistant varieties, intelligent irrigation and monitoring. By analyzing the practical cases of typical cotton-growing areas at home and abroad in water-saving cultivation, sowing period adjustment, heat stress monitoring and precise irrigation, it explores their adaptability and promotion effects. It also looks forward to the future development direction of climate-intelligent cotton planting models based on multi-source data fusion and decision support systems. This study aims to provide theoretical basis and technical support for efficient and sustainable cotton production in the context of addressing climate change.

Keywords Climate-smart agriculture; Cotton cultivation; Drought stress; High-temperature stress; Field management

1 Introduction

Not all crops can be as vulnerable to climate change as cotton. Especially in those arid or semi-arid regions where water resources are already tight and temperatures are relatively high, once extreme weather becomes frequent, it is often these economic crops that rely on stable climate conditions that are the first to be "injured". Cotton is widely cultivated in over 30 countries around the world, making it a "sensitive indicator" under the fluctuations of climate variation. But the problems are not limited to temperature and rainfall. Soil degradation, the intensification of pests and diseases, and even the vulnerability of farmers themselves at the socio-economic level have all been superimposed on the risks of this industry. It is easy to imagine that relying solely on old methods will not be enough. The entire industry has begun to realize that "how to adapt to climate change" is no longer a problem to be considered in the future, but a reality that must be addressed at present (Khan et al., 2018; Rahman et al., 2020; Asma et al., 2025; Liu et al., 2025).

Drought and high-temperature stress are the most critical abiotic factors restricting global cotton production. From seedling emergence, root development, photosynthesis all the way to boll formation, hardly any of these physiological processes can be completely avoided. If the plants develop slowly, the cotton bolls cannot be retained, and eventually the harvest will not increase. Some years even directly caused significant losses for farmers (Ul-Allah, 2020; Farooq et al., 2023). In the face of these challenges, so-called climate-smart agriculture (CSA) has begun to be mentioned by more people. The core of it is not mysterious. It is to combine water-saving practices, resilient varieties and flexible management to protect cotton fields with a stronger and more futures-adaptive system, and even reduce some greenhouse gas emissions incidentally (Imran et al., 2018).

This study reviews the current and projected impacts of climate change on cotton production, with a focus on drought and high-temperature stresses. It explores the physiological, biochemical and agronomic responses of cotton to these stresses, and highlights the latest advancements in cotton stress resistance breeding and management. This study integrates the evidence of the effectiveness of climate-smart practices, identifies

promising genotypes and technologies, and proposes feasible adaptation strategies to provide a comprehensive framework for stakeholders (farmers, breeders, and policymakers) to implement climate-smart cotton cultivation, ensuring sustainable production and improved livelihoods under changing climate conditions.

2 Physiological Responses of Cotton to Drought and Heat Stress

2.1 Root development and stomatal regulation under water deficit

When there is a shortage of water, cotton has more than one way to deal with it. The most direct one is usually that the root system "roots down" even deeper. In this way, even if the surface cracks, the deep moisture still has a chance to be absorbed. During drought periods, this change in the root system is actually one of the fundamental strategies for cotton to sustain its life. However, the above-ground parts also "subtract" - for instance, the closure of stomata is almost the most common response of the plant. Closing the stomata can reduce water evaporation, but the problem is that it also prevents carbon dioxide from entering, and thus photosynthesis drops. This balance is mainly regulated by abscisic acid (ABA). Although it can save lives, the side effect is that the yield is often sacrificed as well (Ullah et al., 2017). Not all varieties perform the same. Some cotton genotypes can maintain a high stomatal conductance and relative moisture content under pressure, and thus are more drought-tolerant (Anwar et al., 2021).

2.2 Effects of high temperature on photosynthesis, boll retention, and fiber development

When a heat wave hits, the first function of cotton to "fail" is photosynthesis. The incoordination of stomatal switches is one aspect, but the inactivation of key enzymes (such as Rubisco) and the damage to chloroplast structure are actually more fatal internal causes (Carmo-Silva et al., 2012). Further down, as the temperature rises, the flowers and cotton bolls are prone to dropping, the development cycle shorts, and the final harvest is naturally affected. Don't have too much hope for the quality either (Abro et al., 2023). The worst-case scenario is that high temperatures and drought occur simultaneously, causing the retention rate of cotton bolls to drop directly, and the decline in seed cotton yield is almost inevitable (Bista et al., 2024; Zhang et al., 2024).

2.3 Oxidative stress and resistance responses under combined drought and heat stress

Under dual stress, it's not just a matter of water and heat; oxidative stress also rises. Reactive oxygen species (ROS) such as hydrogen peroxide and malondialdehyde began to accumulate in the cells (Zafar et al., 2023), which was another blow to cotton. Some drought-resistant genotypes can rapidly mobilize the defense system. The activities of antioxidant enzymes such as superoxide dismutase and catalase will increase, and the levels of protective metabolites such as proline and phenols will also increase simultaneously (Figure 1) (Sekmen et al., 2014; Hasan et al., 2018). With these biochemical defense lines, plants can somewhat preserve their cellular structure, but this mechanism is not equally effective in all varieties, and the performance differences are quite obvious.

3 Overview of Climate-Smart Agronomic Practices

3.1 Water-saving tillage practices: mulching, ridge-furrow, and deep tillage

Drip irrigation cannot be rolled out everywhere, especially in areas with limited water resources and insufficient investment. At this point, some seemingly "not-so-new" water-saving methods come into play, such as covering the ground with plastic film, deeply loosening the soil or using furrow cultivation. Many experiments have confirmed that they can indeed help cotton fields reduce water evaporation, and some can even improve soil structure and regulate temperature incidentally. Ridge cultivation can also conveniently solve drainage problems in areas with uneven terrain or sudden heavy rain (Khalid et al., 2025). In addition, "labor-saving" management methods such as laser land leveling and less plowing, although not as technologically advanced as drip irrigation, are no less effective in improving water utilization and reducing soil erosion. They are even more suitable for long-term use by small and medium-sized farmers.

3.2 Crop rotation and intercropping strategies to enhance resource use efficiency

It's not that cotton should be planted every year. Sometimes, alternating planting can actually yield better results. For instance, some regions choose to rotate legumes or grains in cotton fields or arrange some cover crops before and after the cotton season. The results show that the soil becomes looser, nutrients are more stable, and pests can

also be suppressed (Vitale et al., 2024). Some farmers have also attempted intercropping cotton with other crops, using limited plots to achieve higher utilization rates. Especially in years when land is tight and the climate fluctuates greatly, this kind of "group planting" appears to be more flexible. Ultimately, these methods are not complicated and do not rely on heavy investment. They are developed through the refinement of experience and data. This type of approach is now also classified as "climate-smart" agriculture, which not only focuses on immediate yields but also cares about soil nutrients, ecological resilience, and carbon emission control (Arshad et al., 2021).

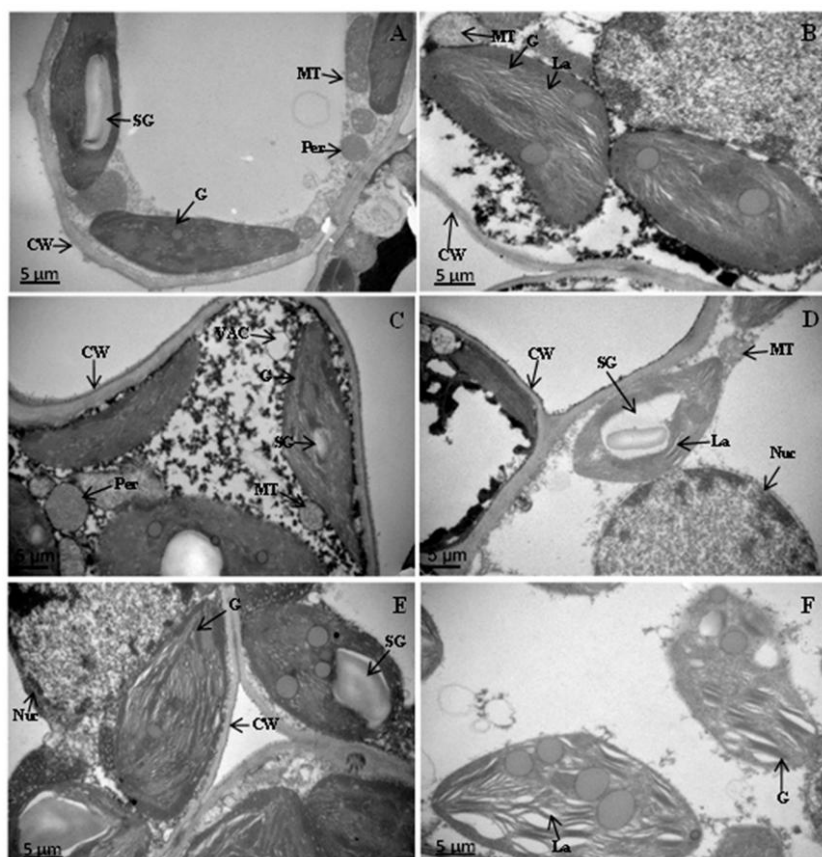


Figure 1 Electron micrographs of leaf mesophyll of cotton species (TM-1, Zhongmian-16 and Pima4-S) under drought stress and control conditions. The TEM micrograph of leaf mesophyll cells of TM-1, Zhongmian-16, and Pima4-S under control shows intact chloroplasts, well-developed grana (G), mitochondria (MC), starch grains (SG) with smooth cell wall (CW), and plasma membrane (PM). (A, Control and B, drought) TEM micrographs of leaf mesophyll cells of TM-1 show oval shaped chloroplast fewer grana (G), swollen mitochondria (MC) with smooth cell wall (CW); (C, control and D, drought) TEM micrographs of leaf mesophyll cell of Zhongmian-16 maintained elongated shape of chloroplast with less dense matrix of grana (G) ruptured cell wall (CW), starch grain (SG), nucleolus present (Nuc), lamella (La) and mitochondria (MC); (E, control and F, drought) TEM micrographs of leaf mesophyll cell of Pima4-S show oval shaped chloroplast fewer grana (G), lamella (La). Scale bars represent 5 μ m (Adopted from Hasan et al., 2018)

3.3 Sowing date adjustment and crop layout optimization to mitigate heat stress

When encountering a heat wave, sometimes it's not something that can be endured by simply putting in effort, but if you plant wisely, you can still avoid some risks. For instance, slightly moving the sowing time forward or backward to avoid the high temperatures during the flowering period of cotton, or adjusting the planting density and widening the row spacing to make the air more circulating and the distribution of sunlight more reasonable, these methods seem simple but have considerable effects. Especially in years with frequent high temperatures, these "folk remedies" are more direct than complex engineering techniques (Engonopoulos et al., 2021). Of course, it doesn't show results every year. However, based on the field records of the past few seasons, the plots that have made these adjustments have indeed seen more stable yields under extreme weather conditions (Wu et al., 2023; Yang and Zhu, 2025).

4 Breeding and Utilization of Stress-Resilient Varieties

4.1 Identification and screening of drought- and heat-tolerant cotton germplasm

Not all cotton varieties perform the same in drought or high temperatures. Some genotypes, such as MNH-786, KAHKSHAN, CEMB-33 and FH-142, have demonstrated stable heat and drought tolerance in multiple experiments and field tests and are regarded as materials worthy of key utilization in future stress-resistant breeding (Reddy et al., 2020; Zafar et al., 2021; Shani et al., 2025). However, it is not the case that stress resistance can be fully judged solely by yield performance. Some materials that seem to grow normally actually lack physiological toughness or fiber stability. Researchers are now also increasingly focusing on metabolic indicators such as proline content and antioxidant enzyme activity to screen genotypes that exhibit stronger stress resistance potential (Majeed et al., 2024).

4.2 Application of marker-assisted selection in stress resistance improvement

The goals of drought resistance and heat resistance are not difficult to talk about, but traditional breeding relying solely on field selection is a bit slow. In fact, this issue was noticed by everyone many years ago. After the molecular markers came out, the situation began to change. Technologies such as QTL mapping, GWAS, and transcriptome techniques can now more quickly identify key genes associated with adversity, and when combined with MAS, they can precisely target breeding materials (Rahman et al., 2021; Rasheed et al., 2023; Patil et al., 2024). Of course, MAS itself also has its shortcomings, especially when the target trait is controlled by multiple genes and is also affected by the environment. It is not realistic to rely on it as a single tool to handle everything. But when it is used in combination with traditional breeding methods, it can indeed significantly accelerate the process. As for CRISPR/Cas9, many studies have now begun to attempt to apply it to stress response genes for direct "point-to-point" gene editing (Ahmed et al., 2024; Luqman et al., 2025). Compared with traditional screening, this approach has a shorter path and may be an even more important step in the future.

4.3 Evaluation of ecological adaptability of stress-resilient cultivars across regions

It's easy to select the varieties and they can be planted in different places. Whether they all "adapt to the soil and water" is another matter. Sometimes, a material that performs exceptionally well in one place may fail when viewed from a different dimension. Breeders have witnessed this kind of thing too many times. Therefore, regional adaptability tests are an indispensable step. Generally, several places with significant differences in ecological conditions are found, and the same batch of materials are planted together. In recent years, technology has also advanced. Drones have entered the fields to help capture some indicators that were previously invisible to the human eye, such as canopy temperature and photosynthetic activity (Farooq et al., 2023; Gu et al., 2024). These high-throughput phenotypic analyses, in combination with multi-point field trials, enable researchers to more precisely determine whether this material is suitable for promotion to arid or high-temperature areas and whether it can maintain a stable yield. In the current context where climate change is becoming increasingly unreasonable, making such a judgment is actually of great significance for breeding decisions (Shahzad et al., 2022).

5 Smart Irrigation and Field Management Technologies

5.1 Design and control of sensor-based precision irrigation systems

When to water the fields and how much to water is actually much more complicated than it sounds. Abnormal climate, differences in plots, and ever-changing crop demands make judgments based on experience, which is often not very reliable. In some places, excessive irrigation not only wastes water but also easily causes diseases. If the irrigation is insufficient, the crops won't grow well. At this point, the intervention of the sensor system becomes even more valuable. They can collect real-time information such as soil moisture and temperature. The background system, in combination with the Internet of Things and the embedded control platform, decides whether to irrigate and how much water to irrigate. Some systems have also integrated fuzzy logic or rule-based algorithms, enabling them to automatically adjust their plans based on the status of the plots without the need for constant human supervision. Although this type of method did not become widespread overnight, it is indeed replacing the previous practice of managing irrigation based on intuition, especially in areas with tight water resources or high production requirements, where it is more favored (Bin et al., 2023; Guo and Chen, 2024; Zhu and Luo, 2025).

5.2 Irrigation model optimization based on soil moisture and weather data

The traditional judgment of irrigation timing often relies on experience, but it is inadequate in responding to extreme weather. Nowadays, irrigation models can integrate data from soil moisture, weather forecasts and the physiological state of crops to more accurately predict the optimal time and amount of irrigation. It is worth mentioning that machine learning and reinforcement learning algorithms have been introduced into such systems. Compared with the previous models based on fixed rules, they perform better in terms of adaptability and prediction accuracy. This algorithm is not only adaptable to the temperature or humidity changes of the day, but also can learn the reaction characteristics of different plots over a long period of time, providing managers with more reliable decision-making basis (Bounajra et al., 2024; Madhuri et al., 2024; Chen et al., 2025).

5.3 Real-time monitoring of heat stress using remote sensing and UAVs

Heat stress is not always visible. Sometimes the surface of the cotton field is calm, but in fact, the plants have long been "weak from the heat". It is difficult to detect problems in the first place by manual field patrol, especially when the area is large, it is easier to miss anomalies. However, remote sensing and unmanned aerial vehicles are different. After they fly around once, data such as canopy temperature, soil moisture and plant growth conditions are all available, and they are all high-definition images. In some cases, the system has already identified the "early signals" of heat stress even before a human response. However, merely monitoring is not enough. Once it can be integrated with the precise irrigation system, water will follow the field that is most "hot" first. This approach is more economical and effective than watering the entire field in a one-size-fits-all manner. Especially in years when heat waves are becoming increasingly common, this approach is indeed crucial for maintaining production (Morchid et al., 2024; Shaikh and Bansod, 2024).

6 Case Studies: Field Practices for Managing Drought and Heat Stress

6.1 Precision water-saving cultivation models in arid cotton areas of Northwest China

Insufficient water is not a new problem in cotton-growing areas like Xinjiang. Farmers have long been accustomed to being thrifty under limited conditions. So-called precise water conservation did not have a mature model from the very beginning; most of the time, it was a case of feeling one's way forward. Operations like delaying the first irrigation and allowing plants to adapt to a brief drought during the seedling stage may seem simple, but they are indeed useful for enhancing resistance. Studies have simulated that as long as irrigation is properly arranged, water conservation can approach 57%, while production is not significantly affected (Wang et al., 2023; Lin et al., 2024). Of course, the issue of water is often accompanied by insufficient heat. Therefore, many places have tried to switch to early-maturing and cold-tolerant cotton varieties, and at the same time appropriately adjust the sowing time, hoping to find a more stable balance point in the context of both water and temperature shortages (Zhang et al., 2024).

6.2 Management strategies for heat stress adaptation in hot and dry cotton regions of India

Some cotton-growing areas in India are so hot that it's hard to breathe. Coupled with frequent droughts, the pressure on crops can be imagined. Faced with this situation, agricultural management has also begun to make adjustments. For instance, plastic film mulching is used to lock in moisture and lower the temperature, while foliar spraying of antioxidants such as proline or betaine helps crops alleviate the damage caused by high temperatures. Meanwhile, by rationally supplementing nutrients, the physiological state of plants can also be stabilized to a certain extent (Aiswarya et al., 2025). Of course, if these measures are not combined with the drought-resistant varieties selected and bred, their effects will be limited. Research shows that when the two are combined, both fiber quality and yield loss can be significantly controlled (EL Sabagh et al., 2020).

6.3 Integrated application of smart monitoring and stress-resilient breeding in the Southern U.S. cotton belt

In the major cotton-growing areas of the southern United States, the days of relying on "experience-based farming" are gradually passing. Nowadays, there may be many soil moisture sensors hidden in the plots, and the drones flying in the air are not just taking photos - they are collecting real-time data on temperature, humidity and crop conditions (Khalequzzaman et al., 2023). However, relying solely on these "eyes" is not enough. Some growers also combine plant growth regulators, such as methylpiperium, to adjust the growth rhythm of cotton and

help them survive periods of high temperature or drought (Lee et al., 2023). The final key still lies in the quality of the variety itself. If drought-resistant and heat-tolerant varieties are selected, along with these precise management tools, there will be more confidence in dealing with complex climates, and the yield and quality will also be more stable (Figure 2) (Mishra et al., 2017).

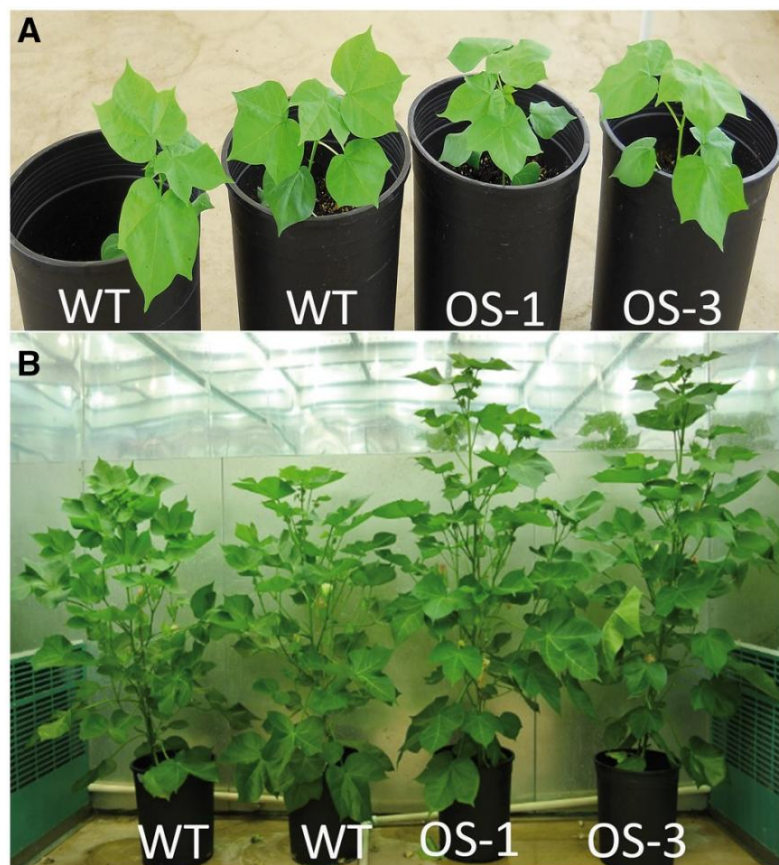


Figure 2 Phenotypes of wild-type and *OsSIZ1*-transgenic cotton plants before and after heat treatment. (A) Before heat treatment. Plants were grown under normal conditions for a month. (B) Plants were treated with heat stress (37°C for 4 h/d) for 45 d before the photograph was taken. WT, wild-type; OS-1 and OS-3, two independent *OsSIZ1*-transgenic lines (Adopted from Mishra et al., 2017)

7 Conclusion and Future Perspectives

Applying climate-smart agriculture (CSA) to cotton production is not a new topic. In the past, it was more like an advocacy, but now it is gradually becoming a practical need. Practices such as adjusting the sowing time, using stress-resistant varieties, and improving irrigation methods may seem ordinary, but they have demonstrated effects of increasing yields, conserving water and fertilizer, and even reducing emissions in many experiments and actual plantations. However, these approaches are not a one-size-fits-all solution. To truly implement them, it still depends on the coordination of localized strategies, the continuous advancement of technology, and the willingness of farmers to give them a try.

Moreover, field management is no longer as simple as relying on "experience in farming". Nowadays, data sources are diverse - weather forecasts, soil moisture monitoring, and crop model outputs, all of which can be integrated into Decision support systems (DSS). Models like DSSAT and APSIM can run simulations in different scenarios and provide reference plans in advance for when to apply nitrogen fertilizer and on which day the sowing effect is best. In addition, with the real-time data integration of ICT tools, the operational space for growers has become much more flexible than before.

What should I do next? I'm afraid there won't be just one way to answer. Sustainable planting, in the final analysis, is a balance achieved through the interplay of multiple factors. Policies must be supportive, technologies must be reliable, and farmers must also be able to see benefits. The terms "water conservation", "precise management" and

"small carbon footprint" may seem far removed from farmland, but once implemented, they can indeed bring about more stable output and lower environmental costs. Therefore, whether applicable combination strategies can be found in different regions, promoted and adhered to is probably the key to determining whether this path can go far.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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