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Innovative Strategies for Mitigating Temperature Stress in Cotton Crop Through Scientific Advances

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Abstract

As climate change continues to have a growing impact on agriculture, mitigating temperature stress in cotton production is crucial. This review outlines a comprehensive heat stress management strategy that encompasses technical enhancements, genetic advancements, and sustainable behaviours. Precision agriculture, which utilises modern sensors, drones, and artificial intelligence, provides real-time data on soil health, enabling farmers to make quick adjustments in response to temperature changes. These techniques enable intelligent modifications in response to changing environmental conditions, thereby enhancing the effectiveness of heat stress mitigation strategies. It is crucial to develop the heat and drought-resistant cotton cultivars. Genetic research, specifically genome-wide association studies (GWAS), has significantly enhanced our understanding of developing temperature-tolerant cotton cultivars, which are essential for adapting to climate change and ensuring a stable global cotton supply. Two examples of environmentally friendly farming practices that can help minimise temperature stress are conservation tillage and cover cropping. These measures not only enhance soil moisture retention but also mitigate the effects of heat stress on cotton plants. Integrated pest management and agroecological approaches promote sustainability by restoring ecosystem balance and reducing chemical use, which benefits both the environment and honeybee populations. This review emphasises the relevance of temperature stress management, precision agriculture, genetic research, and environmentally friendly cotton growing practices. As research and technology continue to advance, these solutions will evolve, enabling the cotton industry to thrive in the face of climate change while maintaining its environmental sustainability.

Keywords *Innovative Strategies, Cotton Crop, Scientific Advances, Mitigating Temperature Stress*

1. Introduction

Cotton is one of the most important crops worldwide, primarily due to its significance for the textile industry and its impact on rural economies (Degefu & Gebregiorgis, 2024). Important species, including *Gossypium hirsutum*, *Gossypium barbadense*, and *Gossypium herbaceum*, significantly contribute to the growth and development of the industry by complementing the fibres used in various textile products (Xing et al., 2024; Ali et al., 2024). However, cotton cultivation presents significant environmental challenges, primarily in the management of water and soil. It has been linked to ecological degradation in areas spanning from Central Asia to tropical Africa and the Americas (Kumar et al., 2024). Harsh climatic conditions pose a threat to the sustainability of cotton. High temperatures during the crucial development stages, mainly flowering, delay fertilisation and thereby reduce boll development, which adversely impacts both yield and fibre quality (Ali et al., 2023). However, when the temperature turns cold, it retards flowering and reduces the length of the fibre, which has an impact on the quality of the cotton delivered (Basra, 2024). High temperatures can further intensify this, increasing the rate of evaporation and altering precipitation, thereby adding complexity to cotton cultivation in water-stressed areas (Xiao et al., 2024). The new approaches are related to the introduction of heat- and cold-stress-tolerant genotypes, adaptation in irrigation techniques, and advancements in pest management technologies (Koramutla et al., 2024; Kundu et al., 2024). Climate-smart agricultural practices, combined with precision farming techniques, can optimise resource use while making cotton crops more resilient to temperature fluctuations (Sarma et al., 2024). Therefore, in light of this, this review aims to summarise the recent scientific breakthroughs that aim to combat the adverse effects of temperature stress on cotton crops by providing an overall overview of strategies developed to improve cotton yield and resilience.

Table 1: Impact of Temperature Stress on Cotton and Adaptive Strategies

Aspect	Details	References
Importance of Cotton	Cotton is a globally significant crop for the **textile industry** and **rural economy**.	Degefu & Gebregiorgis (2024)
Major Cotton Species	- *Gossypium hirsutum* (Upland Cotton) - *Gossypium barbadense* (Egyptian Cotton) - *Gossypium herbaceum* (Levant Cotton)	Xing et al. (2024); Ali et al. (2024)
Environmental Challenges	Cotton cultivation leads to **water and soil management issues**, as well as ecological degradation, across **Central Asia, tropical Africa, and the Americas**.	Kumar et al. (2024)
Impact of High Temperatures	- **Delays fertilisation** during flowering - **Reduces boll development**, affecting **yield and fibre quality**	Ali et al. (2023)
Impact of Cold Temperatures	- **Slows flowering** - **Reduces fibre length**, lowering **cotton quality**	Basra (2024)
Effect of High Evaporation Rates	- **Reduces soil moisture** - **Alters precipitation patterns**, worsening conditions in **water-stressed areas**	Xiao et al. (2024)
Adaptive Strategies	- **Heat- and cold-tolerant genotypes** - **Improved irrigation techniques** - **Advancements in pest management**	Koramutla et al. (2024); Kundu et al. (2024)
Climate-Smart Agricultural Practices	Precision farming optimises resources and enhances resilience against temperature fluctuations.	Sarma et al. (2024)
Objective of Review	Summarises **scientific breakthroughs** in improving **cotton yield and resilience** under temperature stress.	-

2. Understanding Temperature Stress in Cotton

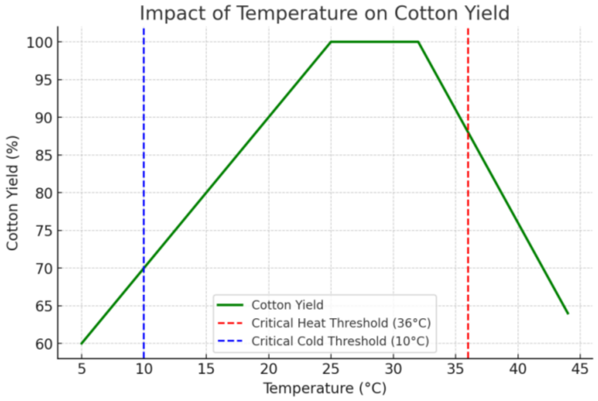
Physiological and Biochemical Responses to Temperature Stress

Cotton is significantly affected in terms of growth and productivity at both cellular and physiological levels due to temperature stress (Zahid et al., 2016). High and low temperatures can disrupt the stability of the membrane structure, causing cells to swell or shrink, which in turn leads to increased permeability and the leakage of ions, as well as essential nutrients (Masoodhu et al., 2024). Proteins are susceptible to high temperatures; a sufficiently high temperature results in denaturation, which is characterised by the breakdown or deactivation of their structural properties and functionality, thereby compromising essential metabolic processes that contribute to homeostasis (Fauvet et al., 2021). The accumulation of reactive oxygen species (ROS) leads to oxidative stress, causing the oxidation of cellular lipids, proteins, and nucleic acids, which can result in protein denaturation following heat shock stimuli (Zou et al., 2025). Cold temperatures slow growth due to a decrease in enzyme activity for metabolic processes and hormone production

(Zhao et al., 2024). In response to these stresses, cotton counteracts through numerous biochemical pathways, including the synthesis of heat shock proteins (HSPs) and antioxidants, which stabilise proteins as well as scavenge reactive oxygen species (ROS), leading to recovery in plants (Patil et al., 2024). Moreover, the performance of photosynthetic machinery is severely impaired under temperature stress, causing damage to vital metabolic processes during photosynthesis, which results in substantial reductions in biomass accumulation and yield (Khan et al., 2024).

Graph 1: Impact of Temperature on Cotton Yield

The graph below represents the impact of **temperature fluctuations** on **cotton yield**. It shows how **yields decrease** when temperatures exceed **optimal conditions (25°C - 32°C)** and highlights the critical loss thresholds beyond **36°C and below 10°C**.



The **graph** illustrating how **temperature variations** impact **cotton yield**:

- **Optimal Temperature (25°C - 32°C)** → Yield remains at **100%**.
- **High-Temperature Stress (>32°C)** → Yield **declines sharply**, with critical losses beyond **36°C**.
- **Cold Stress (<25°C)** → Yield **gradually decreases**, with severe reductions below **10°C**.

Types of Temperature Stress

Cotton crop faces a variety of threats related to heat or cold stress at various growth stages (Wang et al., 2024). Prolonged exposure to temperatures higher than 35 °C leads to heat stress and causes the inhibition of cotton growth, as well as reducing its yield (Angon et al., 2024). Reductions in boll formation and fibre quality are associated with impaired processes of pollen viability and fertilisation that are more likely to be triggered by high temperatures during cardinal stages such as flowering and boll development (Zhang et al., 2024). Heat stress during flowering can reduce cotton seed yield by 50% due to reduced boll retention and fibre development (Patil et al., 2024). In contrast, cold stress responds to cotton at different growth stages. Cold soil temperatures at planting can delay or prevent seed germination and emergence, resulting in uneven stands (Zafar et al., 2024). Cold stress during early growth may result in reduced leaf area and height, leading to stunted plant development, which has a detrimental effect on photosynthesis activity and the overall health of the plants (Lee et al., 2024). In the flowering stage, cold stress is often perceived as causing fruit abortion and decreasing yield; however, its actual effects on pollen germination, which are directly related to reproductive processes, are more pronounced than on boll formation (Gong et al., 2024). The cumulative effect of heat and cold stresses underscores the importance of adaptive management in response, given cotton's sensitivity to temperature fluctuations (Ijaz et al., 2024).

Critical Temperature Thresholds for Cotton

Critical temperature thresholds serve as the basis for executing on-field actions through various means, which can aid in crop management and enhance tolerance and resilience to extreme temperatures in cotton (Neri et al., 2024). There is ample evidence in the literature supporting high temperatures (>35 °C) and low temperatures (<10.0 °C) being responsible for germinative damage to the cotton plants as they are sensitive towards higher air temperatures, particularly during reproductive phases; such atmospheric stress may diminish boll retention and fibre quality along with an increased intensity of boll shedding (Li et al., 2024). For example, temperatures consistently above 36°C during flowering can lead to substantial reductions in seed cotton yield, with potential losses ranging from 20% to 40% depending on the duration and intensity of heat exposure (Beegum et al., 2024). Similarly, cold temperatures below 10 °C are detrimental to cotton (Gossypium hirsutum), as they slow the germination rate and impair seedling development, leading to high seed mortality before emergence and reduced plant stand establishment (Zafar et al., 2024). An important strategy for cotton production in regions with variable climates is the management of surrogate critical temperature thresholds through cultivar selection, agronomic practices, or protective measures (Malashin et al., 2024).

Table 2: Temperature Stress in Cotton and Genetic Approaches

Category	Key Information	References
Physiological and Biochemical Effects	High and low temperatures **disrupt membrane stability**, leading to **ion leakage and nutrient loss**.	Zahid et al. (2016); Masoodhu et al. (2024)
	Protein denaturation occurs under high temperatures, affecting metabolic functions and plant homeostasis.	Fauvet et al. (2021)
	Reactive Oxygen Species (ROS) accumulation leads to oxidative stress, damaging cellular structures.	Zou et al. (2025)
	Cold temperatures **reduce enzyme activity**, slowing	Zhao et al.

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	metabolic functions and hormone production.	(2024)
	Cotton responds by synthesising **heat shock proteins (HSPs) and antioxidants**, stabilising proteins and scavenging ROS.	Patil et al. (2024)
Types of Temperature Stress	**Heat stress:** Temperatures above **35°C** inhibit growth, reduce yield, and impair pollen viability.	Wang et al. (2024); Angon et al. (2024)
	Heat stress during **flowering** can reduce cotton seed yield by **50%** due to boll retention issues.	Patil et al. (2024)
	Cold stress: Low soil temperatures can delay germination, resulting in poor plant stand establishment.	Zafar et al. (2024)
	Cold stress during **early growth** reduces **leaf area, height, and photosynthetic activity**, stunting plant development.	Lee et al. (2024)
	Cold stress **affects pollen germination**, resulting in reproductive issues and reduced yields.	Gong et al. (2024)
Critical Temperature Thresholds	Temperatures above **36°C** reduce **boll retention and fibre quality**, resulting in a **yield loss of 20-40%**.	Beegum et al. (2024)
	Temperatures below **10°C** slow germination, impair seedling development and increase seedling mortality.	Zafar et al. (2024)
	Managing temperature thresholds through **cultivar selection and agronomic practices** is essential for cotton sustainability.	Malashin et al. (2024)

3. Genetic Approaches

Breeding for Heat and Cold Tolerance

Cotton breeding for heat and cold tolerance has traditionally employed conventional methods, including no-tillage planting and selecting the best characteristics among parent plants to form crosses (Zhang et al., 2020). These methods may be time-consuming, but they serve as significant ways to help enhance stress tolerance (Coleman-Derr & Tringe, 2014). Conventional breeding methods involve selecting individual plants with stress resistance based on phenotype and crossing to combine valuable traits (Begna, 2021). U.S. researchers are conducting extensive work to develop heat-tolerant cotton cultivars using these methods, which have successfully led to the development of cultivars conferring dramatic yield increases (Singh et al., 2007). For instance, breeding lines have been developed in India that can resist both heat stress and climate change (Yadav et al., 2022). Traditional methods have been employed in China to produce cold-tolerant varieties that can be grown even at high latitudes (Zhang et al., 2024). While successfully making headway in these areas, classical breeding methods are limited by their speed, and the limitations that this includes have given rise to a move towards more advanced techniques (Ahmar et al., 2020).

GMO—Genetic Manipulation and Biotechnology

Modern biotechnology and genetic engineering have provided a significant impetus for developing varieties resistant to high-temperature stresses (Endo et al., 2009). Among these, CRISPR/Cas9 gene editing technology is one of the most effective tools for modifying genes related to stress responses, resulting in cotton plants that exhibit improved heat and cold tolerance (Khan et al., 2023). The knockdown of genes that are destructive components and affect stress responses has been performed using CRISPR/Cas9, resulting in cotton being able to grow better at high temperatures (Choudry et al., 2024). Moreover, genes conferring heat tolerance are also involved in the development of transgenic cotton varieties. For example, heat-stress-responsive genes such as HSP101 and fibre yield-increasing genes are inserted into the transgenic cotton, which enhances thermotolerance and increases fibre length, respectively (Long et al., 2023). Other techniques based on biotechnology, such as RNA interference (RNAi), have also been employed to reduce the expression of genes associated with temperature stress tolerance responses, which may provide an additional level of control in developing thermotolerant plants (Zhu et al., 2024). These technologies provide the potential for robust cotton genotypes along with high productivity in extreme temperature conditions (Wang et a. 2022).

Molecular markers and genomic selection

Molecular markers and genomic selection are now widely recognised as important tools for expediting cotton breeding programs with improved temperature tolerance (Yang et al., 2023). Molecular markers, such as Simple Sequence Repeats (SSRs) and Single Nucleotide Polymorphisms (SNPs), facilitate the identification of traits responsible for temperature tolerance, allowing breeders to select plants possessing these genes with desirable characteristics (Hasan et al., 2021). Having markers enables the selection of plants with positive genotypic traits, resulting in increased breeding efficiency and decreased times for new variety development (Nadeem et al., 2018). A number of genes that confer heat and cold tolerance have been identified using marker-assisted selection (MAS) methods to breed more tolerant lines in cotton, thereby extending the growing season beyond normal conditions (Ali et al., 2023). Genomic selection enhances this

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process by utilising high-density marker data and a genetic prediction model to more accurately predict the performance of breeding lines, facilitating rapid and accurate improvement (Kumar et al., 2024). Molecular markers, genomic selection, and traditional breeding methods offer a comprehensive approach to enhancing the temperature tolerance trait of cotton, ensuring its steady production output (Gosa et al., 2019).

Table 3: Genetic & Biotechnological Approaches for Temperature Tolerance

Category	Key Information	References
Conventional Breeding for Heat & Cold Tolerance	**No-tillage planting and crossbreeding** have improved stress tolerance but are time-consuming.	Zhang et al. (2020); Coleman-Derr & Tringe (2014)
	U.S. researchers have developed **heat-tolerant cotton cultivars**, resulting in a significant increase in yield.	Singh et al. (2007)
	India and China have produced **climate-resilient cotton varieties**.	Yadav et al. (2022); Zhang et al. (2024)
Genetic Engineering (GMO) & Biotechnology	**CRISPR/Cas9 gene editing** has improved cotton's **heat and cold tolerance**.	Khan et al. (2023)
	Gene knockdown using **CRISPR/Cas9** has enhanced cotton growth under high temperatures.	Choudry et al. (2024)
	Transgenic cotton varieties with **HSP101 genes** improve heat tolerance and fibre quality.	Long et al. (2023)
	RNA interference (RNAi) is being used to reduce gene expression associated with stress responses.	Zhu et al. (2024)
Molecular Markers & Genomic Selection	**SSRs and SNP markers** help identify stress-tolerant traits, improving breeding efficiency.	Hasan et al. (2021)
	Marker-Assisted Selection (MAS) has successfully developed heat- and cold-resistant cotton varieties.	Ali et al. (2023)
	Genomic selection uses genetic prediction models to improve breeding accuracy.	Kumar et al. (2024)
	Combining molecular markers, genomic selection, and breeding enhances cotton resilience to extreme temperatures.	Gosa et al. (2019)

4. Agronomic Practices

Optimizing Planting Dates

The modification of planting dates has a great impact on sustainable cotton for survival under temperature extremes (Anwar et al. 2020). This data can be used to minimize the influence of temperature stress on cotton by avoiding those extreme temperatures, like sowing schedules, in order not to sow during extreme cases or periods when it gets cold or hot (Hussain et al. 2020). An example of this would be early planting, which can help cotton escape the maximal temperature stress during summer and is vital for regions that experience acute heat stress (Pettigrew 2002). To the contrary, if planting is delayed until after all danger of frost has passed, injury from cold spells may be avoided and plant establishment promoted (Richards 1991). Research has shown that the optimal time for planting not only optimizes crop yields but also helps alleviate the negative impacts of extreme temperatures by allowing key growth processes to occur at milder temperatures (Zhang et al., 2019). Therefore, a reasonable planting date can achieve the purpose of alleviating cotton temperature stress and stable yields.

Mulches and ground cover

The use of mulch and ground cover is an important technique for controlling soil temperature, which directly affects cotton growth and stress tolerance (El-Beltagi et al., 2022). Mulches will keep the soil warm, preventing temperature variations that can harm cotton plants (Kader et al., 2017). Organic mulching, such as straw and wood chips, not only modifies the temperature but also ameliorates soil water storage and suppresses weedy pressure, which will, in turn, stimulate cotton production (El-Beltagi et al., 2022). Ground-covered crops also serve a similar function; they can effectively shade the soil and reduce heat absorption during high-temperature periods, thereby maintaining a more stable soil temperature (Jagtap and Jones 1989). The application of mulch and ground cover in cotton management practices mitigates the impact of temperature stress, thereby improving crop yield (Zhang et al., 2023).

Table 4: Agronomic Practices for Temperature Stress Management in Cotton

Agronomic Practice	Key Benefits	References
Optimising Planting Dates	- Adjusting sowing time helps **avoid extreme heat and cold periods**. - **Early planting** allows cotton to escape high summer temperatures. Delayed planting helps avoid frost damage and promotes plant establishment.	Anwar et al. (2020); Hussain et al. (2020); Pettigrew (2002); Zhang et al. (2019)
Mulches & Ground Cover	- **Regulates soil temperature**, reducing fluctuations that stress plants. - **Organic mulching (e.g., straw, wood chips)** enhances soil water storage and weed control. - **Ground-cover crops** reduce heat absorption and maintain stable soil temperatures.	El-Beltagi et al. (2022); Kader et al. (2017); Jagtap & Jones (1989); Zhang et al. (2023)
Irrigation Management	- **Proper irrigation timing** ensures plants have sufficient water to withstand heat stress. - **Drip irrigation** provides **precise water delivery**, reducing water loss. - Enhances **cotton yield and quality** by preventing dehydration during critical growth stages.	Ahmad et al. (2020); Hussain et al. (2020); Liu et al. (2017)

Irrigation Management

Controlled irrigation management is crucial for mitigating heat stress in cotton crops. High temperature damage can be alleviated by providing sufficient and timely irrigation, which enables cotton plants to perform their physiological activities commonly in heat without dehydration (Ahmad et al., 2020). The use of drip irrigation enables precise water application, thereby reducing the amount of leftover soil moisture (Hussain et al., 2020). Studies show that adequately scheduled irrigation not only improves the plant's ability to withstand heat stress in cotton but also ultimately increases crop yield and quality by preventing water stress during the relevant growth stages of plants (Liu et al., 2017). Under these circumstances, effective irrigation management is essential for sustaining cotton productivity in a warm climate.

Crop rotation and intercropping

Integrating cotton with other crops through crop rotation and intercropping is highly effective in reducing temperature stress (Lv et al., 2023). Moreover, likewise, the alternation of cotton between these different generations would increase soil health and management of pests as well as diseases that would eventually benefit improving the quality of growth in terms of production (Deguine et al., 2009). Intercropping with other heat-resistant crops can also offer extended benefits, such as shading and lower soil temperatures, where cotton plants are cultivated (Grigorieva et al., 2023). In the case of cotton, intercropping with legumes or cover crops can enhance straw structure and water retention, as well as mitigate temperature stress (Adetunji et al., 2020). It improves cotton's resilience to temperature stress and, in the long run, contributes to more sustainable and productive systems in cultivated areas (Rahman et al., 2020).

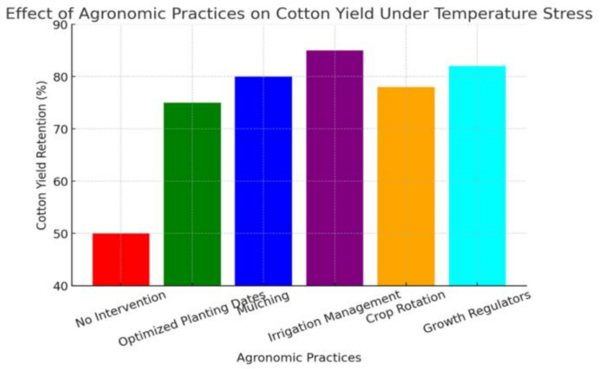
Growth Regulators and Bio-stimulants

The use of growth regulators and bio-stimulants will help increase the stress tolerance of cotton plants to high temperatures (Sarwar et al. 2021). Plant hormones, play a crucial role in biotic and abiotic stress responses (Ku et al. 2018). For example, it has been reported that growth regulators (e.g., gibberellins and cytokinins) can enhance plant development and physiological processes, which leads to greater stress tolerance in plants (Sabagh et al. 2021). The nutrient uptake and stress tolerance mechanisms in the cotton plant can be enhanced by the application of seaweed extracts, amino acids, or other organic bio-stimulants (Rai et al. 2021). These treatments are used to give cotton plants the capability of enduring temperature fluctuations by helping healthy plant development and enhancing overall vigour (Rajesaheb et al. 2024). The use of growth regulators and bio-stimulants in cotton production will assist with the plant's response to suboptimal environmental conditions, which can result in better crop performance (Rai et al. 2021).

Table 5: Sustainable & Advanced Agronomic Techniques

Agronomic Practice	Key Benefits	References
Crop Rotation & Intercropping	- **Rotating cotton with other crops** improves **soil health and pest control**. - **Intercropping with heat-resistant crops** provides **shade and reduces soil**	Lv et al. (2023); Deguine et al. (2009); Grigorieva et al. (2023); Adetunji et

	temperature. - Improves **straw structure, water retention, and temperature resilience**.	al. (2020); Rahman et al. (2020)
Growth Regulators & Bio-Stimulants	**Gibberellins and cytokinins** enhance plant development and stress tolerance. - **Seaweed extracts & amino acids** improve **nutrient uptake and plant vigor**. - Helps cotton **endure temperature fluctuations** and promotes healthy growth.	Sarwar et al. (2021); Ku et al. (2018); Sabagh et al. (2021); Rai et al. (2021); Rajesaheb et al. (2024)



Graph 2: Effect of Agronomic Practices on Cotton Yield Under Temperature Stress

The **bar graph** showing the impact of different **agronomic practices** on **cotton yield retention** under **temperature stress**:

- **No intervention** → Cotton yield drops to **50%** due to heat/cold stress.
- **Optimized planting dates** → Helps avoid extreme temperatures, improving yield to **75%**.
- **Mulching & ground cover** → Enhances soil temperature control, retaining **80% of yield**.
- **Irrigation management** → Ensures water availability, boosting yield retention to **85%**.
- **Crop rotation & intercropping** → Improves soil conditions, sustaining **78% yield**.
- **Growth regulators & bio-stimulants** → Enhance stress tolerance, leading to **82% yield retention**.

5. Advances in Soil and Water Management

Soil Amendments

Use of soil amendments, both organic and inorganic among other advantages can mitigate the consequences due to temperature stress by improving soil structure and ameliorating anything that may be contributing towards abnormal temperatures (Chukwudi et al. 2021). Soil structure and temperature regulation are better when organic amendments such as manure or compost increase the biological content of soil through microbial activity, water-holding capacity (Rastogi et al. 2023). Making pre-plant sub surface amendments improves temperature extremes by providing a more level soil environment which can help minimize heat stress on cotton plants (Yesuf et al. 2020). Inorganic amendments, such as lime and gypsum may also be used to improve soil properties by adjusting pH levels for temperature moderation (Shruthi et al. 2024). In this study, the authors aim to provide evidence of how pharmaceuticals and cosmetics can be successfully utilized as soil amendments in an effort to foster a more temperature resilient environment for growing cotton.

Water Retention Technologies

For instance, water-saving technologies are needed to battle drought-induced heat stress in the cultivation of cotton (Khan et al. 2018). Efficient water retention technologies like soil moisture sensors, drip irrigation systems and the use of hydrogels are set to enhance more efficient utilization so as to mitigate against drought conditions (Fang 2023; Xu et al. 2020; Schuck et al. 2005). They provide realtime soil data on water content facilitating efficient management of irrigation which reduces wastage while maintaining a sufficient moisture level during heat waves (Antonelli et al. 2023). The system can deliver the irrigation water directly to root zones of plants, lower evaporation loss and higher watering efficiency (Chai et al. 2016). Hydrogel technologies increase the water in soil by absorption, and slowly releasing moisture when dry conditions (Neethu et al. 2018). The paper discusses how these techniques provide sustainability in cotton production under drought conditions and alleviate the effects of heat stress.

Microclimate Modification

The management of temperature stress in cotton cultivation can be ameliorated by introducing microclimate modification techniques, such as shelterbelts, shade nets, and reported mulches (Biswas et al., 2023). Windbreaks are trees or shrubs planted around cotton fields that decrease wind speed which lowers the occurrence of soil erosion and promote a more stable microclimate (Brandle et al. 2021). Shade nets may be employed for the partial shading of cotton plants to mitigate direct sunlight and decrease soil, air temperature (Patil et al. 2024). Reflective mulches are applied on the soil surface that reflects solar radiation, resulting in soil temperature reduction (and heat stress mitigation) and promotes a healthier cotton plant (Prem et al. 2020). Altogether, these practices promoted a better microclimate by constituting the abiotic environment around cotton which in-turn promotes thermo-tolerance and carmine-coloration of plants, considerably supporting quality performances. **Graph 3: Impact of Soil and Water Management on Temperature Stress Reduction in Cotton**

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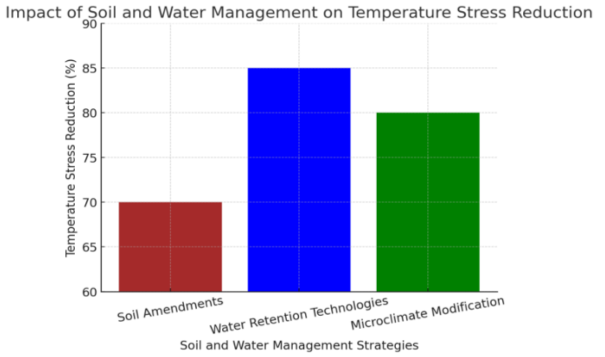

This graph illustrates the impact of various soil and water management strategies on **reducing temperature stress** in cotton crops.

- **Soil Amendments** (e.g., manure, compost, lime) → **70% stress reduction**.
- **Water Retention Technologies** (e.g., drip irrigation, hydrogels) → **85% stress reduction**.
- **Microclimate Modification** (e.g., shade nets, windbreaks) → **80% stress reduction**.

6. Future Perspectives and Emerging Technologies

Precision Agriculture

Sensors, drones, and artificial intelligence (AI) technologies are changing cotton farming into precision agriculture that can monitor temperature stress accurately (SS VC et al. 2024). Sensors deliver data about soil moisture, temperature, and the health of plants in real-time to enable site-specific management interventions (Paul et al. 2022). In terms of crop management, drones fitted with certain sensors like thermal imaging can identify locations experiencing negative heat loads and offer aerial views of the field to allow for specific site monitoring (Khanal et al. 2017). The application process involves using AI-driven analytics to interpret large volumes of data collected by sensors and drones around temperature stress patterns, which can then be targeted for specific management strategies (Peñailillo et al. 2024). Together, these advanced technologies contribute to better thermal management of cotton crops and thus make agriculture more efficient and sustainable.

Cotton Varieties for Drought-Tolerance

Developing climate-resilient cotton varieties is a major focus of research aimed at producing cultivars capable of withstanding multiple environmental stresses (Zafar et al. 2023). Ongoing research includes breeding programs and genetic modifications to enhance cotton's tolerance to heat, drought, and other climatic challenges (Mubarik et al. 2020). Techniques such as genome-wide association studies (GWAS) and marker-assisted selection (MAS) are used to identify and incorporate stress-tolerant traits into cotton varieties (Yasir et al. 2022). Additionally, transgenic approaches are exploring the introduction of genes associated with stress resistance, such as those encoding heat shock proteins and antioxidant enzymes, to develop more resilient cotton varieties (Salman et al. 2019). These efforts are crucial for ensuring the sustainability of cotton production under changing climatic conditions.

Sustainable farm practices

This integrates temperature mitigation strategies into sustainable agriculture, which is crucial for long-term resilience in cotton farming (Srivastav et al. 2021). Sustainable practices are likely to consist of temperature management as a part of the broader farm management plans that address environmental, economic, and social dimensions (Zhen et al. 2005). These include conservation tillage practices, which help promote soil health by reducing heat stress, and the use of cover crops to enhance soil moisture management and temperature regulation (Bezboruah et al. 2024). Additionally, the use of integrated pest management (IPM) and agro-ecological practices keeps environmental balance to avoid heavy dependence on chemical inputs, ensuring farm sustainability as well (Lamichhane et al. 2017; Ekström and Ekbom 2011). Temperature mitigation is essential to climate-smart agriculture and helps not only in building resilience against temperature extremes but also in fostering environmental stewardship (Scherr et al. 2012).

7. Conclusion

Climate change is hitting agriculture hard all over the world, and soon we will face a huge crisis in cotton farming due to temperature stress. A multi-faceted solution of technological advancements combined with genetic solutions and sustainable agricultural practices is key to effectively dealing with these issues. No place has perhaps benefited quite as much from technological advances in agricultural practice as precision agriculture—the agricultural use of technology to manage temperature stress. Advanced technologies use sensors, drones, and artificial intelligence to provide farmers with instant insights on soil moisture levels, soil temperature, and plant health. By using those tools, we are able to produce timely and targeted interventions that can be used for management strategies with high efficiency. It enables much better decision-making, and we are able to respond far more adaptively to changing environmental conditions. Regarding climate change issues, it is important to develop new cotton varieties capable of resisting unavoidable exposure harm in the context of reversed-concept agriculture. So, along the road of genetic study advancement, especially toward breeding due to its technology described (genetic engineering), the cotton crop is mostly in way for cultivars with heat/drought resistance. Indeed, these are the types of innovations that will be crucial for cotton production to cope with growing climate change variability and continue to provide demand from around the world. Sustainable agricultural practices are also important for mitigating the negative effects of temperature stress and maintaining a healthy farm overall. Soil health practices such as conservation tillage and cover cropping improve soil structure, which benefits regulation of water holding capacity dependent on the ability to utilize moisture from wanes or under stress. Furthermore, integrated pest management (of which agro-ecological approaches are part) helps to conserve ecosystem balance and reduce the dependence on chemicals. More sustainable practices have the added benefit of helping mitigate environmental impacts and ensure farm viability in years to come. Overall, concurrently integrating precision agriculture technologies with genetic improvements and various sustainable practices constitutes a complete approach to mitigating temperature stress in the cotton production sector. Using these strategies allows the cotton industry to become climate resilient, maintain yield, and encourage sustainable farming. Advancements in research and technology are improving the approach to these strategies as we continue into a future where cotton farming will be better equipped to support our environment, withstanding increasing variability from continued long-term shifts.

References

1. Adetunji AT, Ncube B, Mulidzi R, Lewu FB (2020) Management impact and benefit of cover crops on soil quality: A review. Soil Tillage Res 204:104717. https://doi.org/10.1016/j.still.2020.104717
2. Ahmad F et al (2020) Heat Stress in Cotton: Responses and Adaptive Mechanisms. In: Ahmad, S., Hasanuzzaman, M. (eds) Cotton Prod Uses. Springer, Singapore, pp 393-428. https://doi.org/10.1007/978-981-15-1472-2_20
3. Ahmar S, Gill RA, Jung KH, Faheem A, Qasim MU, Mubeen M, Zhou W (2020) Conventional and molecular techniques from simple breeding to speed breeding in crop plants: recent advances and future outlook. Int J Mol Sci 21(7):2590. https://doi.org/10.3390/ijms21072590
4. Ali Z, Maryam H, Saddique MA, Ikram RM (2023) Exploiting genetic diversity in enhancing phenotypic plasticity to develop climate-resilient cotton. Genet Resour Crop Evol 70(5):1305-20. https://doi.org/10.1007/s10722-023-01554-3
5. Ali Z, Talpur FN, Afridi HI, Ahmed F, Brohi NA, Abbasi H (2024) Analytical approaches and advancement in the analysis of natural and synthetic fiber: a comprehensive review. Spectrochim Acta A Mol Biomol Spectrosc 326:125164. https://doi.org/10.1016/j.saa.2024.125164
6. Angon PB, Das A, Roy AR, Khan JJ, Ahmad I, Biswas A, Pallob AT, Mondol M, Yeasmin ST (2024) Plant development and heat stress: role of exogenous nutrients and phytohormones in thermotolerance. Discov Plants 1(1):17. https://doi.org/10.1007/s44372-024-00020-3
7. Antonelli A, Farina M, Mininni AN, Calabrese G, Spennacchio M, Tataranni G et al (2023) Effects of Intercropping on Crop Productivity and Land Equivalent Ratio: A Systematic Review and Meta-Analysis. Agronomy 13(8):2113. https://doi.org/10.3390/agronomy13082113
8. Anwar MR, Wang B, Li Liu D, Waters C (2020) Late planting has great potential to mitigate the effects of future climate change on Australian rain-fed cotton. Sci Total Environ 714:136806. https://doi.org/10.1016/j.scitotenv.2020.136806
9. Basra A (2024) Cotton fibers: Dev Biol Quality Improvement Textile Process. CRC Press, Boca Raton https://doi.org/10.1201/9781003578437
10. Beegum S, Reddy KR, Ambinakudige S, Reddy V (2024) Planting for perfection: How to maximize cotton fiber quality with the right planting dates in the face of climate change. Field Crops Res 315:109483. https://doi.org/10.1016/j.fcr.2024.109483
11. Begna T (2021) Conventional breeding methods widely used to improve self-pollinated crops. Int J Res 7(1):1-6. https://doi.org/10.20431/2454-6224.0701001
12. Bezboruah M, Sharma SK, Laxman T, Ramesh S, Sampathkumar T, Gulaiya S, Malathig G, Krishnaveni SA (2024) Conservation Tillage Practices and Their Role in Sustainable Farming Systems. J Exp Agric Int 46:946-59. https://doi.org/10.9734/jeai/2024/v46i92892
13. Biswas P, Mondal S, Maji S, Mondal A, Bandopadhyay P (2023) Microclimate Modification in Field Crops: A Way Toward Climate-Resilience. In: Hasanuzzaman M. (eds) Climate Resilient Agric. Springer, Cham, pp 647–666 https://doi.org/10.1007/978-3-031-37424-1_29
14. Brandle JR, Takle E, Zhou X (2021) Windbreak practices. North Am Agrofor pp 89-126. https://doi.org/10.1002/9780891183785.ch5
15. Chai Q, Gan Y, Zhao C et al (2016) Regulated deficit irrigation for crop production under drought stress. A review. Agron Sustain Dev 36:3. https://doi.org/10.1007/s13593-015-0338-6
16. Choudry MW, Riaz R, Nawaz P et al (2024) CRISPR-Cas9 mediated understanding of plants' abiotic stress-responsive genes to combat changing climatic patterns. Funct Integr Genomics 24:132. https://doi.org/10.1007/s10142-024-01405-z
17. Chukwudi UP, Kutu FR and Mavengahama S (2021) Influence of Heat Stress, Variations in Soil Type, and Soil Amendment on the Growth of Three Drought–Tolerant Maize Varieties. Agronomy 11(8):1485. https://doi.org/10.3390/agronomy11081485
18. Coleman-Derr D, Tringe SG (2014) Building the crops of tomorrow: advantages of symbiont-based approaches to improving abiotic stress tolerance. Front Microbiol 5:283. https://doi.org/10.3389/fmicb.2014.00283
19. Degefu DT, Gebregiorgis ZD (2024) Cotton Biotechnology. In Murugesh BK, Kabish AK, Tesema GB, Semahagn BK (eds) Cotton Sect Dev Ethiopia Textile Sci Clothing Technol, pp 65-68 https://doi.org/10.1007/978-981-99-9149-5_4
20. Deguine JP, Ferron P, Russell D (2009) Sustainable pest management for cotton production: a review. Sustain Agric pp 411-42. https://doi.org/10.1007/978-90-481-2666-8_27

*Corresponding Author: **Muhammad Ahmad Saeed**

21. Ekström G, Ekbom B (2011) Pest control in Agro-ecosystems: An ecological approach. Crit Rev Plant Sci 30(1–2):74–94. https://doi.org/10.1080/07352689.2011.554354
22. El-Beltagi HS, Basit A, Mohamed HI, Ali I, Ullah S, Kamel EA, Shalaby TA, Ramadan KM, Alkhateeb AA, Ghazzawy HS (2022) Mulching as a sustainable water and soil saving practice in agriculture: A review. Agronomy 12(8):1881 https://doi.org/10.3390/agronomy12081881
23. Endo WB, Enfors SO, Fiechter A, Hoare M, Mattiasson B, Sahm H, Schiigerl K, Stephanopoulos G, yon Stockar U (2009) Adv Biochem Eng Biotechnol. Springer, Heidelberg https://doi.org/10.1007/3-540-36488-9
24. Fang H (2023) Actionable Science for Irrigation. In: Sun, Z. (eds) Actionable Sci Global Environ Change. Springer, Cham, pp 203-228. https://doi.org/10.1007/978-3-031-41758-0_8
25. Fauvet B, Rebeaud ME, Tiwari S, De Los Rios P, Goloubinoff P (2021) Repair or degrade: the thermodynamic dilemma of cellular protein quality-control. Front Mol Biosci 8:768888. https://doi.org/10.3389/fmolb.2021.768888
26. Gong Z, Zheng J, Yang N, Li X, Qian S, Sun F, Geng S, Liang Y, Wang J (2024) Whole-Genome Bisulfite Sequencing (WGBS) Analysis of *Gossypium hirsutum* under High-Temperature Stress Conditions. Genes 15(10):1241. https://doi.org/10.3390/genes15101241
27. Gosa SC, Lupo Y, Moshelion M (2019) Quantitative and comparative analysis of whole-plant performance for functional physiological traits phenotyping: new tools to support pre-breeding and plant stress physiology studies. Plant Sci 282:49-59. https://doi.org/10.1016/j.plantsci.2018.05.008
28. Grigorieva E, Livenets A, Stelmakh E (2023) Adaptation of agriculture to climate change: A scoping review. Clim 11(10):202. https://doi.org/10.3390/cli11100202
29. Hasan N, Choudhary S, Naaz N, Sharma N, Laskar RA (2021) Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes. J Genet Eng Biotechnol 19(1):128. https://doi.org/10.1186/s43141-021-00231-1
30. Hussain S et al (2020) Irrigation Scheduling for Cotton Cultivation. In: Ahmad S, Hasanuzzaman M (eds) Cotton Prod Uses. Springer, Singapore pp 59-80 https://doi.org/10.1007/978-981-15-1472-2_5
31. Ijaz A, Anwar Z, Ali A, Ditta A, Shani MY, Haidar S, Wang B, Fang L, Khan SM, Khan MK (2024) Unraveling the genetic and molecular basis of heat stress in cotton. Front Genet 15:1296622. https://doi.org/10.3389/fgene.2024.1296622
32. Jagtap SS, Jones JW (1989) Stability of crop coefficients under different climate and irrigation management practices. Irrig Sci 10:231–244. https://doi.org/10.1007/BF00257955
33. Kader MA, Senge M, Mojid MA, Ito K (2017) Recent advances in mulching materials and methods for modifying soil environment. Soil Tillage Res 168:155-66. https://doi.org/10.1016/j.still.2017.01.001
34. Khan A, Xudong P, Ullah N et al (2018) Coping with drought: stress and adaptive mechanisms, and management through cultural and molecular alternatives in cotton as vital constituents for plant stress resilience and fitness. Biol Res 51:47. https://dx.doi.org/10.1186/s40659-018-0198-z
35. Khan N, Choi SH, Lee CH, Qu M, Jeon JS (2024) Photosynthesis: Genetic Strategies Adopted to Gain Higher Efficiency. Int J Mol Sci 25(16):8933. https://doi.org/10.3390/ijms25168933
36. Khan Z, Khan SH, Ahmed A, Iqbal MU, Mubarik MS, Ghouri MZ, Ahmad F, Yaseen S, Ali Z, Khan AA, Azhar MT (2023) Genome editing in cotton: challenges and opportunities. J Cotton Res 6(1):3. https://doi.org/10.1186/s42397-023-00140-3
37. Khanal S, Fulton J, Shearer S (2017) An overview of current and potential applications of thermal remote sensing in precision agriculture. Comput Electron Agric 15(139):22-32. https://doi.org/10.1016/j.compag.2017.05.001
38. Koramutla MK, Ram C, Bhat D, Kumar P, Negi M, Dagla MC, Vasupalli N, Aminedi R (2024) Genome editing as a promising tool to dissect the stress biology. In Curr Omics Adv Plant Abiotic Stress Biol pp 397-417. https://doi.org/10.1016/B978-0-443-21625-1.00027-0
39. Ku YS, Sintaha M, Cheung MY, Lam HM (2018) Plant hormone signaling crosstalks between biotic and abiotic stress responses. Int J Mol Sci 19(10):3206. https://doi.org/10.3390/ijms19103206
40. Kumar R, Das SP, Choudhury BU et al (2024) Advances in genomic tools for plant breeding: harnessing DNA molecular markers, genomic selection, and genome editing. Biol Res 57:80. https://doi.org/10.1186/s40659-024-00562-6
41. Kumar S, Anusha BS, Bhatia A (2024) Soil, Water, and Crop Management Practices to Mitigate Greenhouse Gases Emission. In: Rahman MM, Biswas JC, Meena RS (eds) Clim Change Soil Water Plant Nexus. Springer, Singapore, pp 189-222 https://doi.org/10.1007/978-981-97-6635-2_7
42. Kundu S, Saini DK, Meena RK et al (2024) High-throughput phenotyping and AI technologies for deciphering crop resilience to heat stress. Plant Physiol Rep 29:699–715. https://doi.org/10.1007/s40502-024-00821-4
43. Lamichhane JR (2017) Pesticide use and risk reduction in European farming systems with IPM: An introduction to the special issue. Crop Prot 97:1-6. http://dx.doi.org/10.1016/j.cropro.2017.01.017

*Corresponding Author: **Muhammad Ahmad Saeed**

44. Lee Z, Lim J, Harikrishna J et al (2024) Regulation of Plant Responses to Temperature Stress: A Key Factor in Food Security and for Mitigating Effects of Climate Change. Int J Plant Prod 18:141–159. https://doi.org/10.1007/s42106-024-00282-7
45. Li W, Wu B, Hu B, Wan Y, Wang J, Jia M (2024) Effects of Defoliation at Different Fertility Stages on Material Accumulation, Physiological Indices and Yield of Cotton. Agric 14(2):258. https://doi.org/10.3390/agriculture14020258
46. Liu C, Qi Z, Gu Z, Gui D, Zeng F (2017) Optimizing irrigation rates for cotton production in an extremely arid area using RZWQM2-simulated water stress. Trans ASABE 60(6):2041-52. https://doi.org/10.13031/trans.12365
47. Long Y, Qin Q, Zhang J, Zhu Z, Liu Y, Gu L, Jiang H, Si W (2023) Transcriptomic and weighted gene co-expression network analysis of tropic and temperate maize inbred lines recovering from heat stress. Plant Sci 327:111538. https://doi.org/10.1016/j.plantsci.2022.111538
48. Lv Q, Chi B, He N, Zhang D, Dai J, Zhang Y, Dong H (2023) Cotton-based rotation, intercropping, and alternate intercropping increase yields by improving root–shoot relations. Agronomy 13(2):413. https://doi.org/10.3390/agronomy13020413
49. Malashin I, Tynchenko V, Gantimurov A, Nelyub V, Borodulin A, Tynchenko Y (2024) Predicting sustainable crop yields: Deep learning and explainable AI tools. Sustainability 16(21):9437. https://doi.org/10.3390/su16219437
50. Masoodhu SS, Natarajan N, Vasudevan M (2024) Modification of bentonite with black cotton soil and carboxyl methyl cellulose for the enhancement of hydraulic performance of geosynthetic clay liners. Water Sci Technol 89(7):1846-59. https://doi.org/10.2166/wst.2024.093
51. Mubarik MS, Ma C, Majeed S, Du X, Azhar MT (2020) Revamping of cotton breeding programs for efficient use of genetic resources under changing climate. Agronomy10(8):1190. https://doi.org/10.3390/agronomy10081190
52. Nadeem MA, Nawaz MA, Shahid MQ, Doğan Y, Comertpay G, Yıldız M, Hatipoğlu R, Ahmad F, Alsaleh A, Labhane N, Özkan H (2018) DNA molecular markers in plant breeding: current status and recent advancements in genomic selection and genome editing. Biotechnol Biotechnol Equip 32(2):261-85. https://doi.org/10.1080/13102818.2017.1400401
53. Neethu TM, Dubey PK, Kaswala AR (2018) Prospects and Applications of Hydrogel Technology in Agriculture. Int J Curr Microbiol App Sci 7(05):3155-3162. https://doi.org/10.20546/ijcmas.2018.705.369
54. Neri P, Gu L, Song Y (2024) The effect of temperature on photosystem II efficiency across plant functional types and climate. Biogeosciences 21(11):2731-58. https://doi.org/10.5194/bg-21-2731-2024
55. Patil AM, Pawar BD, Wagh SG, Shinde H, Shelake RM, Markad NR, Bhute NK, Červený J, Wagh RS (2024) Abiotic Stress in Cotton: Insights into Plant Responses and Biotechnological Solutions. Agric 14(9):1638. https://doi.org/10.3390/agriculture14091638
56. Patil AM, Pawar BD, Wagh SG, Shinde H, Shelake RM, Markad NR, Bhute NK, Cervený J, Wagh RS (2024) Abiotic Stress in Cotton: Insights into Plant Responses and Biotechnological Solutions. Agric 14:1638. https://doi.org/10.3390/agriculture14091638
57. Paul K, Chatterjee SS, Pai P, Varshney A, Juikar S, Prasad V, Bhadra B, Dasgupta S (2022) Viable smart sensors and their application in data driven agriculture. Comput Electron Agric 1(198):107096. https://doi.org/10.1016/j.compag.2022.107096
58. Peñailillo FF, Gutter K, Vega R, Silva GC (2024) Transformative Technologies in Digital Agriculture: Leveraging Internet of Things, Remote Sensing, and Artificial Intelligence for Smart Crop Management. J Sens Actuator Netw 13(4):39. https://doi.org/10.3390/jsan13040039
59. Pettigrew WT (2002) Improved yield potential with an early planting cotton production system. Agron J 94(5):997-1003. https://doi.org/10.2134/agronj2002.9970
60. Prem M, Ranjan P, Seth N, Patle GT (2020) Mulching techniques to conserve the soil water and advance the crop production—A Review. Curr World Environ 15:10-30. http://dx.doi.org/10.12944/CWE.15.Special-Issue1.02
61. Rahman MH et al (2020) Climate Resilient Cotton Production System: A Case Study in Pakistan. In: Ahmad S, Hasanuzzaman M (eds) Cotton Prod Uses. Springer, Singapore, pp 447-484 https://doi.org/10.1007/978-981-15-1472-2_22
62. Rai N, Rai SP, Sarma BK (2021) Prospects for abiotic stress tolerance in crops utilizing phyto-and bio-stimulants. Front Sustain Food Syst 5:754853. https://doi.org/10.3389/fsufs.2021.754853
63. Rajesaheb KS, Subramanian S, Boominathan P, Thenmozhi S, Gnanachitra M (2024) Bio-stimulant in improving crop yield and soil health. Commun Soil Sci Plant Anal 56(3):464–499. https://doi.org/10.1080/00103624.2024.2416925
64. Rastogi, Mausmi, Verma, Shikhar et al (2023) Soil Health and Sustainability in the Age of Organic Amendments: A Review. Int J Environ Clim Change, 13 (10): 2088-2102. https://doi.org/10.9734/ijecc/2023/v13i102870
65. Richards RA (1991) Crop improvement for temperate Australia: future opportunities. Field

Crops Res 26(2):141-69. https://doi.org/10.1016/0378-4290(91)90033-R

66. Sabagh AE, Mbarki S, Hossain A, Iqbal MA, Islam MS, Raza A, Llanes A, Reginato M, Rahman MA, Mahboob W, Singhal RK (2021) Potential role of plant growth regulators in administering crucial processes against abiotic stresses. Front Agron 3:648694. https://doi.org/10.3389/fagro.2021.648694
67. Salman M, Majeed S, Rana IA, Atif RM, Azhar MT (2019) Novel Breeding and Biotechnological Approaches to Mitigate the Effects of Heat Stress on Cotton. In: Wani, S. (eds) Recent Approaches Omics Plant Resilience Climate Change. Springer, Cham, pp 251-277 https://doi.org/10.1007/978-3-030-21687-0_11
68. Sarma HH, Borah SK, Dutta N, Sultana N, Nath H, Das BC (2024) Innovative approaches for climate-resilient farming: strategies against environmental shifts and climate change. Int J Environ Climate Change 14(9):217-41. https://doi.org/10.9734/ijecc/2024/v14i94407
69. Sarwar M, Saleem MF, Ali B, Nadeem M, Ghani MA, Zhou W, Islam F (2021) Improving thermotolerance in Gossypium hirsutum by using signalling and non-signalling molecules under glass house and field conditions. Ind Crops Prod 172:113996. https://doi.org/10.1016/j.indcrop.2021.113996
70. Scherr SJ, Shames S, Friedman R (2012) From climate-smart agriculture to climate-smart landscapes. Agric Food Secur 1:12. https://doi.org/10.1186/2048-7010-1-12
71. Schuck EC, Frasier WM, Webb RS, Ellingson LJ, Umberger WJ (2005) Adoption of More Technically Efficient Irrigation Systems as a Drought Response. Int J Water Resour Dev 21(4):651–662. https://doi.org/10.1080/07900620500363321
72. Shruthi, Prakash NB, Dhumgond P et al (2024) The benefits of gypsum for sustainable management and utilization of acid soils. Plant Soil 504:5–28. https://doi.org/10.1007/s11104-024-06907-0
73. Singh RP, Prasad PV, Sunita K, Giri SN, Reddy KR (2007) Influence of high temperature and breeding for heat tolerance in cotton: a review. Adv Agron 93:313-85. https://doi.org/10.1016/S0065-2113(06)93006-5
74. Srivastav AL, Dhyani R, Ranjan M et al (2021) Climate-resilient strategies for sustainable management of water resources and agriculture. Environ Sci Pollut Res Res 28:41576–41595. https://doi.org/10.1007/s11356-021-14332-4
75. SS VC, Hareendran A, Albaaji GF (2024) Precision farming for sustainability: An agricultural intelligence model. Comput Electron Agric 226:109386. https://doi.org/10.1016/j.compag.2024.109386
76. Wang Y, Zafar N, Ali Q, Manghwar H, Wang G, Yu L, Ding X, Ding F, Hong N, Wang G, Jin S (2022) CRISPR/Cas genome editing technologies for plant improvement against biotic and abiotic stresses: advances, limitations, and future perspectives. Cells 11(23):3928. https://doi.org/10.3390/cells11233928
77. Wang Z, Peng Z, Khan S, Qayyum A, Rehman A, Du X (2024) Unveiling the power of MYB transcription factors: Master regulators of multi-stress responses and development in cotton. Int J Biol Macromol 276:133885. https://doi.org/10.1016/j.ijbiomac.2024.133885
78. Xiao J, Chen Y, Hu C, Zhu Z, Liu B (2024) Inspired by Plant Transpiration: Fabrication of a Unique Micro–Nano-Structured Janus Evaporator Using Waste Cotton Fabric for Enhanced Efficiency and Salt Resistance. ACS Sustain Chem Eng 12(6):2364-74. https://doi.org/10.1021/acssuschemeng.3c07157
79. Xing B, Li P, Li Y, Cui B, Sun Z, Chen Y, Zhang S, Liu Q, Zhang A, Hao L, Du X (2024) Integrated transcriptomic and metabolomic analysis of *Gossypium hirsutum* and *Gossypium barbadense* responses to verticillium wilt infection. Int J Mol Sci 26(1):28. https://doi.org/10.3390/ijms26010028
80. Xu L, Abbaszadeh P, Moradkhani H, Chen N, Zhang X (2020) Continental drought monitoring using satellite soil moisture, data assimilation, and an integrated drought index. Remote Sens Environ 250:112028. https://doi.org/10.1016/j.rse.2020.112028
81. Yadav MR, Choudhary M, Singh J, Lal MK, Jha PK, Udawat P, Gupta NK, Rajput VD, Garg NK, Maheshwari C, Hasan M (2022) Impacts, tolerance, adaptation, and mitigation of heat stress on wheat under changing climates. Int J Mol Sci 23(5):2838. https://doi.org/10.3390/ijms23052838
82. Yang Z, Gao C, Zhang Y, Yan Q, Hu W, Yang L, Wang Z, Li F (2023) Recent progression and future perspectives in cotton genomic breeding. J Integr Plant Biol 65(2):548-69. https://doi.org/10.1111/jipb.13388
83. Yasir M, Kanwal HH, Hussain Q, Riaz MW, Sajjad M, Rong J, Jiang Y (2022) Status and prospects of genome-wide association studies in cotton. Front Plant Sci 13:1019347. https://doi.org/10.3389/fpls.2022.1019347
84. Yesuf HM, Xiaohong Q, Jhatial AK (2020) Advancements in Cotton Cultivation. In: Cotton Sci Process Technol Gene Ginning Garment Green Recycling. Springer, Singapore, pp 39–59 https://doi.org/10.1007/978-981-15-9169-3_3
85. Zafar MM, Chattha WS, Khan AI, Zafar S, Subhan M, Saleem H et al (2023) Drought and heat stress on cotton genotypes: Suggested agro-physiological and biochemical features for climate resilience.

*Corresponding Author: **Muhammad Ahmad Saeed**

Front Plant Sci 14:1265700. https://doi.org/10.3389/fpls.2023.1265700

86. Zafar S et al (2024) Plant Growth Under Extreme Climatic Conditions. In: Fahad S, Saud S, Nawaz T, Gu L, Ahmad M, Zhou R (eds) Environ Climate Plant Vegetat Growth. Springer Nature, Switzerland, pp 133-178 https://doi.org/10.1007/978-3-031-69417-2_5
87. Zahid KR, Ali F, Shah F, Younas M, Shah T, Shahwar D, Hassan W, Ahmad Z, Qi C, Lu Y, Iqbal A (2016) Response and tolerance mechanism of cotton *Gossypium hirsutum L.* to elevated temperature stress: a review. Front Plant Sci 7:937. https://doi.org/10.3389/fpls.2016.00937
88. Zhang D, Zhang Y, Sun L, Dai J, Dong H (2023) Mitigating salinity stress and improving cotton productivity with agronomic practices. Agronomy 13(10):2486. https://doi.org/10.3390/agronomy13102486
89. Zhang J, Li XM, Lin HX, Chong K (2019) Crop improvement through temperature resilience. Annu Rev Plant Biol 70(1):753-80. https://doi.org/10.1146/annurev-arplant-050718-100016
90. Zhang J, Loka DA, Wang J, Ran Y, Shao C, Tuersun G, Li Y, Wang S, Zhou Z, Hu W (2024) Co-occurring elevated temperature and drought stress inhibit cotton pollen fertility by disturbing anther carbohydrate and energy metabolism. Ind Crops Prod 208:117894. https://doi.org/10.1016/j.indcrop.2023.117894
91. Zhang X, Zhang J, Khan A, Zhu D, Zhang Z (2024) Improving the productivity of Xinjiang cotton in heat-limited regions under two life history strategies. J Environ Manag 363:121374. https://doi.org/10.1016/j.jenvman.2024.121374
92. Zhang X, Zhang Z, Zhou R, Wang Q, Wang L (2020) Ratooning annual cotton (Gossypium spp.) for perennial utilization of heterosis. Front Plant Sci 11:554970. https://doi.org/10.3389/fpls.2020.554970
93. Zhao N, Geng Z, Zhao G et al (2024) Integrated analysis of the transcriptome and metabolome reveals the molecular mechanism regulating cotton boll abscission under low light intensity. BMC Plant Biol 24:182. https://doi.org/10.1186/s12870-024-04862-7
94. Zhen L, Routray JK, Zoebisch MA, Chen G, Xie G, Cheng S (2005) Three dimensions of sustainability of farming practices in the North China Plain: a case study from Ningjin County of Shandong Province, PR China. Agric Ecosyst Environ 105(3):507-22. https://doi.org/10.1016/j.agee.2004.07.012
95. Zhu X, Li W, Zhang N, Jin H, Duan H, Chen Z, Chen S, Wang Q, Tang J, Zhou J, Zhang Y (2024) StMAPKK5 responds to heat stress by regulating potato growth, photosynthesis, and antioxidant defenses. Front Plant Sci 15:1392425. https://doi.org/10.3389/fpls.2024.1392425
96. Zou Y, Cao P, Bao Z, Xu Y, Xu Z, Guo H (2025) Histological, physiological and transcriptomic analysis in hepatopancreas of Procambarus clarkii under heat stress. Ecotoxicol Environ Saf 289:117459. https://doi.org/10.1016/j.ecoenv.2024.117459

