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Climate-Ready Crops: Exploring Heat-Tolerant Alleles for Future Farming

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Global climate models forecast more frequent and intense heat waves that will increasingly intersect with crop growing seasons (Mahajan *et al*., 2025). Heat stress reduces photosynthetic rates, accelerates phenological development, and shortens grain-filling periods, all of which lead to yield penalties. In many crops the reproductive stage is the most temperature-sensitive period, and even short episodes of high temperature can cause spikelet sterility or fruit abortion (Malumpong *et al*.,2019). Traditional breeding and agronomic adjustments alone are unlikely to meet the scale and speed of the challenge, motivating a genetics-centric approach that harnesses heat-tolerant alleles (Isnaini *et al*., 2023). Modern genomic tools including GWAS, QTL mapping, pan-genomics, and genome editing enable accelerated discovery and deployment of alleles that improve thermotolerance (Huang *et al*., 2023). Integrating physiological knowledge with molecular genetics and farmer-preferred traits is essential to deliver climate-ready cultivars that are adoptable in diverse production systems

Climate-ready cultivar

A climate-ready cultivar is a genetically improved crop variety capable of maintaining stable yield under climate-induced stresses such as heat, drought, salinity, irregular rainfall, and emerging pests. These cultivars carry favourable alleles, QTLs, and stress-responsive genes that enhance photosynthesis, membrane stability, reproductive thermotolerance, and water-use efficiency. Developed through modern breeding tools such as marker-assisted selection, genomic selection, pan-genomics, speed breeding and genome editing combined with classical breeding, climate-ready cultivars play a vital role in climate-smart agriculture and long-term food security.

In the context of "Climate-Ready Crops: Exploring Heat-Tolerant Alleles for Future Farming," these cultivars represent the strategic deployment of heat-responsive genes and molecular pathways to future-proof agriculture against intensifying thermal stress conditions, ensuring food system resilience and productivity in warming agro-ecosystems.

Understanding Heat Stress in Crops (Physiological Impacts)

- **Photosynthesis and Carbon Assimilation:** Heat destabilizes PSII, reduces Rubisco activation, and increases photorespiration, lowering CO_2 assimilation (Mahajan *et al*., 2025). It decreases chlorophyll, damages thylakoids, accelerates senescence (Khan *et al*., 2019), and alters carbon partitioning, reducing biomass.
- **Membrane Integrity and Cellular Stability:** High temperature increases membrane fluidity and ion leakage (Sangwan *et al*., 2022), promotes ROS accumulation, and

intensifies lipid peroxidation (Ding *et al.*, 2024). Damage to chloroplast and mitochondrial membranes reduces ATP generation and photosynthesis.

- **Reproductive Failure and Yield Loss:** Heat reduces pollen viability, anther dehiscence, and fertilization (Hunter *et al.*, 2018). QTLs such as qHTSF explain variation in spikelet fertility (Kumar *et al*., 2021). Grain filling is impaired, lowering grain weight and yield.
- **Water Relations and Canopy Cooling:** Heat raises transpiration demand, induces stomatal closure, and limits CO_2 uptake (Wu *et al.*, 2025). Canopy temperature depression indicates thermotolerance, with cooler canopies linked to better yield stability.

Understanding Heat Stress in Crops (Molecular Impacts):

- **Heat Sensing and Early Signaling:** Heat perception through membrane changes and Ca^{2+} influx activates MAPKs (Kang *et al*., 2023) and induces HSFs (Tian *et al*., 2021). Early ROS act as secondary messengers (Suzuki *et al*., 2018).
- **Heat Shock Factors (HSFs) and Gene Regulation:** HSFs regulate the heat shock response by binding Heat Shock Elements and inducing HSP expression (Tian *et al.*, 2018). Their isoform-specific and tissue-specific roles allow fine-tuning of heat responses (Liu *et al*., 2020). Variations in HSFs among genotypes correlate with thermotolerance through improved protein protection and oxidative balance.
- **Heat Shock Proteins (HSPs) and Chaperone Function:** HSP70, HSP90, HSP100, and small HSPs function as chaperones that prevent protein misfolding and assist in refolding denatured proteins under heat stress (Malkeyeva *et al*., 2025). Favorable HSP alleles enhance survival and yield under high temperatures. Small HSPs also protect thylakoid membranes and maintain photosystem stability (Nayak *et al*., 2023).
- **ROS Scavenging and Antioxidant Systems:** Heat stress triggers rapid ROS accumulation in chloroplasts and mitochondria, necessitating enzymatic antioxidants such as SOD, CAT, APX, and GR for detoxification. Genotypic variation in antioxidant capacity contributes significantly to heat tolerance. Non-enzymatic antioxidants ascorbate, glutathione, and tocopherols further maintain cellular redox balance.
- **Membrane Proteostasis and Proteasome Function:** Heat-damaged proteins are degraded via the ubiquitin–proteasome pathway to prevent toxic aggregation (Moyano *et al.*, 2023). Genes such as TT1/TTL1 and specific proteasome subunits regulate protein turnover and membrane stability in crops like rice, contributing to thermotolerance (Cuadrado Pedetti *et al.*, 2021).
- **Osmoprotectants and Metabolic Adjustments:** Under heat stress, plants accumulate osmoprotectants such as proline, glycine betaine, trehalose, and soluble sugars to stabilize proteins and membranes (Singh *et al*., 2023). Proline regulates redox balance and protects enzymes, while glycine betaine and sugars maintain osmotic stability and prevent heat-induced denaturation (Zulfiqar *et al*., 2022).

Modern Breeding Strategies for Climate-Ready Crops:

Modern plant breeding strategies are essential to develop crop varieties that can cope with the unprecedented pace of climate change, especially heat and drought stress, while maintaining yield and quality.

- **Marker-Assisted Selection (MAS):** Marker-Assisted Selection (MAS) uses DNA markers linked to desirable traits to identify superior plants without waiting for phenotypic expression. MAS is widely applied in cereals such as rice and wheat to introgress favourable alleles for heat and drought tolerance (Tomar *et al*., 2021).
- **Genomic Selection (GS):** Genomic Selection (GS) uses genome-wide markers to estimate genomic estimated breeding values (GEBVs) without extensive phenotyping. It is now integrated into climate-smart cereal breeding programs using high-throughput genotyping and predictive modelling (Hafeez *et al*., 2023).

- **Speed Breeding:** Speed breeding manipulates environmental conditions to shorten crop life cycles and achieve multiple generations yearly. This approach rapidly introgresses climate-resilient alleles into elite varieties (Kumar *et al*., 2023).
- **Genome Editing (CRISPR-Cas Systems):** CRISPR/Cas systems allow precise genome modifications to improve traits like heat tolerance and stress resilience. CRISPRa and CRISPRi modulate gene expression without altering DNA, enabling fine control of heat tolerance pathways (Massel *et al*., 2021).
- **Pan-Genomics, High-Throughput Phenotyping, and AI:** Pan-genomics identifies rare stress-adaptive alleles across diverse accessions beyond a single reference genome (Admas *et al*., 2025). Integrating phenomics with genomics and AI improves prediction accuracy for heat tolerance and climate resilience (Pandiyan *et al*., 2025).
- **Participatory and Farmer-Led Breeding:** Participatory breeding involves farmers in variety selection, ensuring relevance to local conditions and increasing adoption of climate-ready cultivars. Farmer-led programs identify traits like heat tolerance, early maturity, and water-use efficiency in specific regions.

Heat-Tolerant Alleles in Major Crops:

- **Rice (*Oryza sativa*):** Rice thermotolerance has several well-characterized loci: *Thermotolerance 1 (TT1), TT2* and *TT3* were isolated from Oryza glaberrima and shown to protect cells via proteasome function, wax metabolism and other pathways that maintain reproductive and vegetative heat tolerance (Huang *et al*., 2023).
- **Wheat (*Triticum aestivum*):** Recent functional genomics work has shown that **TaAP2/ERF family transcription factor genes** regulate heat tolerance during the **grain-filling stage** in wheat, likely through ethylene signalling pathways. Allelic variation in these regulators influences kernel weight, chlorophyll stability, and delayed senescence under heat stress. (Magar *et al*., 2024).
- **Maize (*Zea mays*):** Maize heat tolerance is polygenic, with transcriptomic and QTL studies identifying heat-responsive genes including HSPs, NAC and other transcription factors that preserve kernel set and grain filling under heat (El-Sappah *et al*., 2022).
- **Chickpea (*Cicer arietinum*):** QTL mapping in chickpea has revealed multiple heat-tolerance regions (e.g., *Ca_Heat* loci and QTLs for days-to-flowering and pod set) and candidate genes linked to pollen viability, membrane thermostability and carbohydrate partitioning (Paul *et al*., 2018).
- **Tomato (*Solanum lycopersicum*):** Tomato heat resilience is associated with HSF and HSP gene families (for example *SlyHSF* members and small HSPs) that protect pollen and fruit set under heat; expression profiling and candidate-gene studies have identified specific HSFs upregulated during heat stress (Aldubai *et al*., 2022).

Conclusion

The accelerating pace of global warming presents a formidable threat to agricultural productivity, particularly through recurrent and severe heat stress affecting crop growth, physiology, and reproductive success. Understanding the multifaceted impacts of heat from impaired photosynthesis and membrane destabilization to reproductive failure and oxidative injury highlights the urgent need for genetic solutions that enhance thermotolerance. Advances in genomics, pan-genomics, molecular physiology, and precision breeding have enabled the identification of key heat-tolerant alleles, regulatory networks, and protective pathways across major crops. Modern breeding tools such as MAS, GS, speed breeding, and genome editing are revolutionizing the development of climate-ready cultivars with improved heat resilience, yield stability, and adaptability. Integrating these innovations with farmer-led selection and high-throughput phenotyping will accelerate the delivery of robust, climate-resilient varieties. Ultimately, leveraging heat-tolerant alleles and advanced breeding platforms is essential to safeguard future food security and build sustainable, climate-smart agricultural systems capable of thriving in a warming world.

References

1. Admas, T., Jiao, S., Pan, R. and Zhang, W. (2025). Pan-omics insights into abiotic stress responses: bridging functional genomics and precision crop breeding. *Functional & Integrative Genomics*, **25**(1), 128.
2. Alagawany, M., Farag, M. R., Abd El-Hack, M. E. and Patra, A. (2017). Heat stress: effects on productive and reproductive performance of quail. *World's Poultry Science Journal*, **73**(4), 747-756.
3. Aldubai, A. A., Alsadon, A. A., Migdadi, H. H., Alghamdi, S. S., Al-Faifi, S. A. and Afzal, M. (2022). Response of tomato (*Solanum lycopersicum* L.) genotypes to heat stress using morphological and expression study. *Plants*, **11**(5), 615.
4. Cuadrado-Pedetti, M. B., Rauschert, I., Sainz, M. M., Amorim-Silva, V., Botella, M. A., Borsani, O and Sotelo-Silveira, M. (2021). The arabidopsis tetratricopeptide thioredoxin-like 1 gene is involved in anisotropic root growth during osmotic stress adaptation. *Genes*, **12**(2), 236.
5. Ding, B., Liu, B., Zhu, X., Zhang, H., Hu, R., Li, S. and Hou, L. (2024). Downregulation of the GhROD1 gene improves cotton fiber fineness by decreasing acyl pool saturation, stimulating small heat shock proteins (sHSPs), and reducing H2O2 production. *International Journal of Molecular Sciences*, **25**(20), 11242.
6. El-Sappah, A. H., Rather, S. A., Wani, S. H., Elrys, A. S., Bilal, M., Huang, Q. and Abbas, M. (2022). Heat stress-mediated constraints in maize (*Zea mays*) production: challenges and solutions. *Frontiers in plant science*, *13*, 879366.
7. Hafeez, A., Ali, B., Javed, M. A., Saleem, A., Fatima, M., Fathi, A. and Soudy, F. A. (2023). Plant breeding for harmony between sustainable agriculture, the environment, and global food security: an era of genomics-assisted breeding. *Planta*, **258**(5), 97.
8. Huang, D., Zhang, Z., Fan, Y., Tang, S., Zhuang, J. and Zhu, Y. (2023). Detection of QTL for high-temperature tolerance in rice using a high-density bin map. *Agronomy*, **13**(6), 1582.
9. Hunter, R. H. F. (2018). Temperature gradients in female reproductive tissues and their potential significance. *Animal Reproduction (AR)*, **6**(1), 7-15.
10. Isnaini, I., Nugraha, Y., Baisakh, N. and Carsono, N. (2023). Toward Food Security in 2050: Gene Pyramiding for Climate-Smart Rice. Sustainability (Switzerland), ***15*** (19)
11. Kang, X., Zhao, L. and Liu, X. (2023). Calcium signaling and the response to heat shock in crop plants. *International Journal of Molecular Sciences*, **25**(1), 324.
12. Khalil, A. M. (2020). The genome editing revolution. *Journal of genetic engineering and biotechnology*, **18**(1), 68.
13. Khan, M. A. (2019). *Promoter Characterization and Protein Identification of The PH1 Gene that Regulates Chromosome Pairing in Wheat (Triticum aestivum)*. Washington State University.
14. Kumar, A., Dadheech, A. and Singh, M. (2023). MODERN TECHNIQUES IN PLANT BREEDING-SPEED BREEDING. *Archives of Agriculture and Allied Sciences*.
15. Kumar, A., Gupta, C., Thomas, J. and Pereira, A. (2021). Genetic dissection of grain yield component traits under high nighttime temperature stress in a rice diversity panel. *Frontiers in plant science*, *12*, 712167.
16. Liu, Y., Li, L., Qi, H., Que, H., Wang, W. and Zhang, G. (2020). Regulation between HSF1 isoforms and HSPs contributes to the variation in thermal tolerance between two oyster congeners. *Frontiers in Genetics*, *11*, 581725.
17. Magar, M. M., Liu, H., and Yan, G. (2024). Wheat TaAP2/ERF Genes Regulate Heat Tolerance Through Ethylene Signaling at Grain-Filling Stage. *Journal of Plant Growth Regulation*, **43**(8), 2855-2872.
18. Mahajan, S., Thakur, P., Das, S. *et al.* Impression of contemporary heat stress complexities in agricultural crops: a review. *Plant Growth Regul* (2025).
19. Malkeyeva, D., Kiseleva, E. V. and Fedorova, S. A. (2025). Heat shock proteins in protein folding and reactivation. *Vavilov Journal of Genetics and Breeding*, **29**(1), 7.

20. Malumpong C, Cheabu S, Mongkolsiriwatana C, Detpittayanan W, Vanavichit A (2019). Spikelet fertility and heat shock transcription factor (Hsf) gene responses to heat stress in tolerant and susceptible rice (Oryza sativa L.) genotypes. The Journal of Agricultural Science 157, 283–299.
21. Massel, K., Lam, Y., Wong, A. C., Hickey, L. T., Borrell, A. K. and Godwin, I. D. (2021). Hotter, drier, CRISPR: the latest edit on climate change. *Theoretical and Applied Genetics*, **134**(6), 1691-1709.
22. Mishra, S., Spaccarotella, K., Gido, J., Samanta, I. and Chowdhary, G. (2023). Effects of heat stress on plant-nutrient relations: An update on nutrient uptake, transport, and assimilation. *International Journal of Molecular Sciences*, **24**(21), 15670.
23. Moyano, P., Sola, E., Naval, M. V., Guerra-Menéndez, L., Fernandez, M. D. L. C. and Del Pino, J. (2023). Neurodegenerative proteinopathies induced by environmental pollutants: Heat shock proteins and proteasome as promising therapeutic tools. *Pharmaceutics*, **15**(8), 2048.
24. Nayak, L., Lal, M. K., Tiwari, R. K., Kumar, R., Lal, P., Das, R. and Kumar, A. (2023). A balancing act: exploring the interplay between HSPs and osmoprotectants in temperature stress responses. *South African Journal of Botany*, *162*, 64-71.
25. Pandiyan, I., Shinde, S. G., More, A., Paul, M., Singh, G., Kaur, R. and Singh, H. (2025). Multi-trait breeding for pest resistance, yield and stress tolerance in field crops: a review.
26. Paul, P. J., Samineni, S., Thudi, M., Sajja, S. B., Rathore, A., Das, R. R. and Gaur, P. M. (2018). Molecular mapping of QTLs for heat tolerance in chickpea. *International journal of molecular sciences*, **19**(8), 2166.
27. Sangwan, S., Shameem, N., Yashveer, S., Tanwar, H., Parray, J. A., Jatav, H. S. and Poczai, P. (2022). Role of salicylic acid in combating heat stress in plants: insights into modulation of vital processes. *Frontiers in Bioscience-Landmark*, **27**(11), 310.
28. Singh, M. B. N. (2023). *Osmoadaptation Strategies in Halophilic Bacteria* (Doctoral dissertation, Goa University).
29. Suzuki, N. and Katano, K. (2018). Coordination between ROS regulatory systems and other pathways under heat stress and pathogen attack. *Frontiers in Plant Science*, *9*, 490.
30. Tian, F., Hu, X. L., Yao, T., Yang, X., Chen, J. G., Lu, M. Z. and Zhang, J. (2021). Recent advances in the roles of HSFs and HSPs in heat stress response in woody plants. *Frontiers in plant science*, *12*, 704905.
31. Tomar, S., Babu, M. S., Gaikwad, D. J. and Maitra, S. (2021). A review on molecular mechanisms of wheat (Triticum aestivum L.) and rice (Oryza sativa L.) against abiotic stresses with special reference to drought and heat.
32. Wu, H. C., Yu, S. Y., Vivek, S., Wang, Y. D. and Jinn, T. L. (2025). ABA-mediated regulation of PME12 influences stomatal density, pore aperture, and heat stress response in Arabidopsis thaliana. *Planta*, **261**(2), 29.
33. Zulfiqar, F., Ashraf, M. and Siddique, K. H. (2022). Role of glycine betaine in the thermotolerance of plants. *Agronomy*, **12**(2), 276.