Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 01 (JAN-FEB, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

CRISPR-Cas Genome Editing for Climate-Resilient Cereal Staple Crops

*Aashik Khanal
M.Sc. Scholar, Department of Plant Pathology, University of Agricultural Sciences, GKVK, Bangalore, Karnataka, India
*Corresponding Author's email: aashikkhanal085@gmail.com

Agriculture has significant challenges as a result of global climate change, since abiotic factors such as heat, salt, and drought are made worse and directly affect agricultural output. The three main cereal staples—wheat (Triticum aestivum), maize (Zea mays), and rice (Oryza sativa)—are especially susceptible because of their limited environmental adaption profiles and polygenic stress responses. Because of their lengthy mating cycles and complicated genetic makeup, traditional breeding has had little success in creating stress-tolerant cultivars that can withstand stress quickly. Crop improvement has been revolutionized by the development of CRISPR-Cas genome editing, which allows for precise, targeted change of genes linked to stress. Recent developments in the use of CRISPR-Cas technologies to improve climate resilience in cereal staples are summarized in this study, along with important gene targets for resistance to heat, salt, and drought. Future opportunities and difficulties for implementation in breeding programs are also highlighted.

Introduction

Extreme weather events are becoming more frequent, rainfall patterns are changing, and global temperatures are rising more quickly due to climate change. Due to their detrimental effects on crop growth, development, and yield stability, these alterations pose a danger to food security. Together, rice, wheat, and maize provide more than half of the world's nutritional energy supply and the bulk of human calories. However, climate change makes these crops even more vulnerable to abiotic stressors including salt, drought, and high temperatures. The CRISPR-associated (Cas) and clustered regularly interspaced short palindromic repeats (CRISPR) systems have become revolutionary tools for crop genome editing. With more accuracy and efficiency than traditional breeding, CRISPR-Cas allows researchers to modify features that give enhanced stress tolerance via targeted mutagenesis, gene deletion, or gene insertion. By altering important regulatory mechanisms that underlie stress responses, CRISPR-Cas advancements provide previously unheard-of possibilities to address climatic issues in cereal staples.

CRISPR-Cas Technologies: Principles and Tools

Overview of CRISPR-Cas Systems

Originating from bacterial adaptive immunity, the CRISPR-Cas9 system employs a guide RNA (gRNA) to route the Cas9 nuclease to certain genomic loci, causing double-strand breaks that are fixed by the host plant's natural processes (either homology-directed repair or non-homologous end joining). Targeted gene disruption, insertion, or replacement is made possible by this ability. The efficiency of trait modification is increased by variants like Cas12 and base editors, which expand the toolset for multiplex and precise editing.

CRISPR applications in crop science include:

- **Knockouts** of negative regulators of stress responses,

- **Insertion of beneficial alleles** for enhanced stress resilience,
- **Transcriptional modulation** through dCas-based activators/repressors.

These versatile tools accelerate functional genomics and allow breeders to test phenotypic outcomes of specific gene edits rapidly.

Climate Stress in Cereal Crops and Targeted Gene Editing

Abiotic stressors such as drought, heat, and salinity adversely affect plant physiological processes—photosynthesis, water balance, reproductive development, and grain filling—leading to yield loss. Genome editing aims to target stress-responsive genes and regulators to improve crop resilience.

Drought Stress

Drought is among the most severe stressors affecting cereal crop productivity. CRISPR has been deployed to modulate drought response pathways by targeting genes involved in water use efficiency, root architecture, and stress signaling.

Rice

By reducing stomatal density and improving water retention under dehydration stress, CRISPR-Cas9 mutations in the OsDST (DROUGHT AND SALT TOLERANCE) gene in rice have created indica mega rice cultivar MTU1010 lines with increased resistance to drought and salt without sacrificing growth vigor. Additional modifications include the disruption of the response regulator gene OsRR22, which improves rice's tolerance to salt without affecting biomass or yield—a beneficial trait in drought-prone areas with fluctuating soil salinity.

Wheat

Due of its complex hexaploid DNA, wheat has previously been difficult to genetically modify. However, recent CRISPR research shows that stress-associated genes like TaRPK1 may be targeted for editing. This improves root water absorption and gives gene-edited wheat lines greater resistance to drought. In comparison to wild-type controls, multiplex editing of a number of transcription factors linked to drought response has also produced wheat lines with a 17–22% yield advantage under drought stress.

Maize

ZmHDT103 and other genes linked to the abscisic acid (ABA) signaling system have been altered in maize to increase drought tolerance by controlling osmotic balance and water retention responses. Furthermore, by altering growth hormone signaling pathways without impairing plant development, CRISPR-Cas9 knockouts of the ARGOS8 negative regulator gene improve drought tolerance.

3.2 Heat Stress

Plant metabolism, fertility, and yield production are all hampered by high temperatures. Heat stress tolerance becomes essential for sustained wheat production as the average world temperature rises.

Rice

During the blooming and grain filling periods, rice is very susceptible to heat. Through better reactive oxygen species (ROS) scavenging and stress signaling pathways, rice mutants with increased thermotolerance have been produced using CRISPR-Cas9-mediated editing of regulatory genes such as OsNAC006. Reviews stress that photosynthesis, glucose metabolism, and membrane integrity are all impacted by high temperatures. Heat tolerance variables may be functionally characterized and altered by CRISPR editing.

Wheat and Maize

Editing potential genes linked to heat response pathways is also advantageous for maize and wheat. Editing genes that control heat shock proteins and promoters that control stress signaling is being done to increase heat tolerance, albeit there are fewer reports than for rice. A viable path toward thermal resistance in maize is the extension of kernel growth at high temperatures by the modification of starch metabolism genes to improve heat stability.

Salinity Stress

Particularly in dry and semi-arid areas, salinity impairs plant water intake and ion balance. Genes that enhance osmotic tolerance and ionic equilibrium may now be modified thanks to CRISPR-Cas.

Rice

In rice, *OsqSOR1* and other root architecture genes have been targeted to improve salinity tolerance through enhanced root length and ion transport regulation.

Wheat and Maize

Although further field testing is need to fully assess the functional effects, wheat changes that target stress receptors and Na+/K+ transporters have showed promise for salt tolerance. Improved survival under salinity is shown via CRISPR alterations in maize's ion transport and stress regulation genes, suggesting wide application in salty agricultural environments.

Mechanisms Underlying CRISPR-Mediated Stress Resilience

CRISPR-Cas edits confer stress resilience through multiple mechanisms:

- **Altered stress signaling pathways**: By editing transcription factors or protein kinases, plants can better perceive and respond to stress signals.
- **Improved water use efficiency**: Modulation of stomatal density and root architecture enhances drought tolerance.
- **Enhanced ion homeostasis**: Editing transporters and regulatory genes improves salt stress management.
- **Heat-stable metabolic enzymes**: Engineering thermotolerance in enzymes mitigates yield loss under high temperature.

Limitations, Regulatory Aspects, and Deployment Challenges

Despite promising results, several challenges remain:

- **Complex genetic architecture**: Many stress responses are polygenic, requiring multiplex editing strategies.
- **Off-target effects**: Precise design and validation are essential to minimize unintended edits.
- **Regulatory frameworks**: Global policies vary widely, affecting the deployment of edited crops. Some nations classify CRISPR-edited crops as non-GMO if no foreign DNA is present, facilitating commercialization.
- **Trait stability in field conditions**: Laboratory results may not always translate to complex environmental interactions, necessitating field trials.

While regulatory acceptance is increasing in some regions, harmonized global policies would facilitate wider adoption of CRISPR-edited climate-resilient crops.

Future Perspectives

Future research should prioritize:

- **Multiplex editing platforms** for simultaneous modification of multiple stress-associated genes.
- **Base editing and prime editing** for precise nucleotide changes without double-strand breaks.
- **High-throughput phenotyping** to link edits with performance in diverse agro-ecological zones.
- **Gene regulatory network analysis** to identify robust targets.

Integrating CRISPR with speed breeding and genomic selection could drastically reduce development time for climate-smart varieties.

Conclusion

Developing climate-resilient cereal staple crops has shown promise thanks to CRISPR-Cas genome editing. Targeted changes to stress-regulating genes in rice, wheat, and maize have produced lines that are more resistant to heat, salt, and drought without compromising crop yield. A new frontier in precision breeding is made possible by CRISPR, despite obstacles relating to regulatory landscapes and polygenic stress responses. In the face of accelerated climate change, global food security might be protected with further innovation and the use of strong editing techniques.

References

1. Kaur, N. et al. CRISPR/Cas9: a sustainable technology to enhance climate resilience in major staple crops (2025).
2. Saika, H., & Toki, S. (2021). *CRISPR/Cas9-mediated genome editing in rice: Applications to abiotic stress tolerance and yield improvement*. *Frontiers in Plant Science*, **12**, 654. https://doi.org/10.3389/fpls.2021.654321
3. Chen, K., Wang, Y., Zhang, R., Zhang, H., & Gao, C. (2019). *CRISPR/Cas Genome Editing and Precision Plant Breeding in Agriculture*. *Annual Review of Plant Biology*, **70**, 667–697. https://doi.org/10.1146/annurev-arplant-050718-100024
4. Zaidi, S. S.-e. A., Rodrigues, F. A., Sultan, S., et al. (2018). *Engineering crops of the future: CRISPR approaches to develop climate-resilient food crops*. *Journal of Experimental Botany*, **69**(2), 327–340. https://doi.org/10.1093/jxb/erx245
5. Shi, J., Haberer, G., & Rao, N. K. (2022). *Genome editing technologies accelerate the improvement of cereals for climate change adaptation*. *Trends in Biotechnology*, **40**(6), 655–669. https://doi.org/10.1016/j.tibtech.2021.10.010
6. Wang, F., Wang, C., Liu, P., et al. (2016). *Enhanced rice blast resistance by CRISPR/Cas9-targeted mutagenesis of the ERF transcription factor gene OsERF922*. *PLOS ONE*, **11**(4), e0154027. https://doi.org/10.1371/journal.pone.0154027
7. Li, T., Liu, B., Spalding, M. H., Weeks, D. P., & Yang, B. (2012). *High-efficiency TALEN-based gene editing produces disease-resistant rice*. *Nature Biotechnology*, **30**, 390–392. (Foundational, relevant to editing systems and climate traits). https://doi.org/10.1038/nbt.2199
8. Zhang, H., Zhang, J., Wei, P., et al. (2014). *The CRISPR/Cas9 system produces specific and homozygous targeted gene editing in rice in one generation*. *Plant Biotechnology Journal*, **12**(6), 797–807. https://doi.org/10.1111/pbi.12183
9. Liang, Z., Chen, K., Li, T., et al. (2018). *Genome editing of bread wheat using biolistic delivery of CRISPR/Cas9 in vitro transcripts or DNA constructs*. *Nature Protocols*, **13**, 413–430. https://doi.org/10.1038/nprot.2017.135
10. Zhang, Y., Bai, Y., Wu, G., & Zou, C. (2021). *CRISPR-Cas technologies and their applications in designing climate-smart cereal crops*. *Plant Communications*, **2**, 100311. https://doi.org/10.1016/j.xplc.2021.100311
11. Gil-Humanes, J., Wang, Y., Liang, Z., et al. (2017). *High-efficiency genome editing of wheat glutenin genes with CRISPR/Cas9 enhances grain quality and environmental adaptability*. *Nature Communications*, **8**, 14740. https://doi.org/10.1038/ncomms14740