Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 03 (MAY-JUNE, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Biotechnology in Climate Smart Agriculture

*Dalpat Lal[1], Saumya Gupta[2], Aditi Panpalia[2] and Prerna Dogra[3]
[1]College of Agriculture, Jodhpur, Agriculture University, Jodhpur, India
[2]Jayoti Vidhyapeeth Women University, Jaipur, India
[3]Sri Karan Narendra Agriculture University, Jobner, Jaipur, India
*Corresponding Author's email: dalpat032@gmail.com

Biotechnology plays an important role in Climate-Smart Agriculture (CSA) by helping farming systems adapt to climate change while maintaining productivity and sustainability. Increasing temperatures, irregular rainfall, soil degradation, and rising pest and disease pressures make it difficult for farmers to rely only on traditional farming practices. Biotechnological tools such as molecular breeding, genetic improvement, tissue culture, and genome editing help to develop crop varieties that can tolerate drought, salinity, heat and pests (Pereponova *et al*., 2023). These improved crops allow farmers to maintain stable yields even under changing environmental conditions. Biotechnology also supports sustainable soil and nutrient management. The use of biofertilizers, beneficial microorganisms, and plant growth–promoting bacteria improves soil fertility and enhances nutrient availability to plants. These biological inputs reduce dependence on chemical fertilizers and help lower environmental pollution. Similarly, biopesticides and biological control agents provide eco-friendly solutions for managing pests and diseases, reducing the excessive use of synthetic pesticides (Ejiaz *et al*., 2025).

In addition, biotechnology contributes to better resource-use efficiency in crops, enabling plants to utilize water and nutrients more effectively. This is particularly important in regions facing water shortages and poor soil quality. When biotechnological innovations are combined with climate-smart practices such as precision farming and improved irrigation systems, they strengthen the resilience and sustainability of agricultural systems. Thus, biotechnology serves as a key tool in achieving the goals of Climate-Smart Agriculture by improving productivity, enhancing resilience to climate stress, and promoting environmentally responsible farming (Yuan *et al*., 2024; Ngongolo & Mmbando, 2024). First time CSA framed by the Food and Agriculture Organization (FAO) at the Hague conference in 2010, agricultural systems.

Approaches of Biotechnology in Climate Smart Agriculture

Technologies such as molecular markers, CRISPR-based gene editing, RNA-based pest control, synthetic biology, nanotechnology, and AI-supported crop planning each play a role in strengthening agricultural systems. These tools help improve crop performance, protect plants from pests and diseases, and support better decision-making in farming. In simple terms, biotechnology drives innovation, while CSA provides the direction for applying these innovations effectively. Together, they contribute to building farming systems that are more resilient, productive, and environmentally sustainable over the long term. Some of the biotechnological approaches and examples (Table 1) used in CSA are discussed below.

1. Omics Technologies

Molecular markers are valuable tools in modern crop improvement because they allow breeders to detect useful genetic traits at an early stage of plant development. These DNA markers act as indicators that help scientists identify characteristics such as drought tolerance, disease resistance, yield potential, and grain quality without waiting for the plant to complete its growth cycle. Marker-assisted breeding has therefore made the selection process faster and more efficient (Jain *et al*., 2009). For example, genomic studies in rice have identified important regions like the Sub1A QTL that contribute to flood tolerance (Wang *et al*., 2025). Recent research also shows that advanced approaches such as proteomics and metabolomics are being used to improve nutritional quality and stress tolerance in vegetables and other crops (Bhattarai *et al*., 2025). Similarly, multi-omics studies in crops like chickpea and date palm reveal how plants adjust their biochemical processes to survive drought and salinity (Chowdhury *et al*., 2025). In addition, next-generation sequencing (NGS) has accelerated the development of molecular markers in crops such as millets, enabling faster and more precise breeding (Ajeesh Krishna *et al*., 2022). Overall, integrating multi-omics technologies is becoming an important strategy for sustainable crop improvement and more informed breeding decisions (Syeda, 2025; Rautela *et al*., 2026).

2. Genome Editing Technologies

Genome editing allows scientists to make precise changes in a plant's DNA, similar to carefully editing a specific section of a text rather than altering the entire sequence. Instead of randomly combining genes through traditional breeding, researchers can modify or deactivate particular genes that influence traits such as sensitivity to heat, pests, or salinity. Among the available tools, CRISPR/Cas9 has become the most widely used because it is faster, more affordable, and more accurate than earlier technologies like TALENs and zinc-finger nucleases. Advanced methods such as base editing and prime editing enable even more precise genetic adjustments by altering small DNA sequences. For example, researchers improved the fragrance of rice by modifying the OsBADH2 gene, which increased the production of the aromatic compound 2-acetyl-1-pyrroline (Shan *et al*., 2015). Gene editing has also been used to improve drought tolerance in maize by targeting genes such as ZmHDT103, which enhances water-use efficiency (Rao *et al*., 2022). Similar approaches have been applied in other crops, including editing TaHSP17 in wheat to improve heat tolerance and SOS1 in barley to strengthen resistance to saline conditions (Khalid *et al*., 2026). Because these techniques allow targeted improvements without long breeding cycles, they are becoming important tools for developing climate-resilient crops. Recent studies and scientific reviews highlight CRISPR-based technologies as a key component of modern climate-smart biotechnology (Chen, 2025). In addition, researchers in several Asian programs have used CRISPR to develop tomato plants that can better withstand multiple stresses, including drought and soil salinity (Gatica-Arias & Hernández-Soto, 2025).

3. Marker Assisted Selection and Genomic Selection

Marker-assisted selection (MAS) and genomic selection (GS) are widely regarded as advanced breeding approaches. In MAS, breeders use specific DNA markers associated with desirable traits—such as resistance to pests or flooding—to guide their selection process. GS expands on this by analyzing the entire genome and applying predictive models to identify young plants with strong future performance, reducing both time and resource use. The use of genome-wide technologies and high-quality sequencing data is helping improve traits like drought tolerance and nutritional value, particularly in semi-arid agricultural systems, thereby supporting CSA (Wambi *et al*., 2021). Evidence shows that these approaches have been effectively applied in crops such as rice, wheat, and maize to enhance drought resilience, yield consistency, and nutrient use efficiency (Mmbando, 2025). In coffee producing regions of Brazil and Africa, integrating MAS and GS has led to the development of Coffea canephora varieties that are more tolerant to heat and pests while maintaining high bean quality. This advancement contributes to more stable farmer incomes (Ferrão *et al*., 2024). Likewise, in dry regions of Africa and Asia, researchers are applying genome-wide tools to improve finger millet, developing varieties that are both drought-tolerant and nutritionally enhanced, which helps smallholder farmers achieve more reliable harvests under unpredictable rainfall conditions (Wambi *et al*., 2021).

4. RNA Interference and Gene Silencing

RNA interference (RNAi) functions as a temporary gene-silencing mechanism within plant cells. Rather than altering the DNA permanently, it suppresses the activity of specific genes, particularly those linked to viruses or insect pests. Because of this targeted action, RNAi offers a more environmentally sustainable option compared to intensive pesticide use, especially in areas where climate change is increasing pest pressure.

Researchers are actively exploring RNAi-based strategies in crops such as cassava and various fruit species to safeguard yields while reducing reliance on chemical inputs. In plant biotechnology, RNAi is often described as a link between conventional breeding and modern molecular approaches, as it enables control over gene expression without causing major genetic alterations (Rajput *et al*., 2021). Studies also show that double-stranded RNA (dsRNA) can function as a biological control agent against insects, nematodes, and plant pathogens. This has led to the development of sprayable RNA-based treatments, known as spray-induced gene silencing (SIGS), which can be applied directly to crops (Zotti *et al*., 2018). Beyond pest management, RNAi has broader applications in crop improvement. Research indicates its role in enhancing nutritional value, reducing allergenic components, and increasing beneficial plant compounds, contributing to both higher productivity and improved food quality (Saurabh *et al*., 2014). At the same time, efforts are underway to refine the precision of RNAi technology. Ongoing research focuses on optimizing the design and delivery of small interfering RNAs to minimize off-target effects, ensuring that only specific genes related to pests or environmental stress are silenced (Neumeier & Meister, 2021).

Precision and Digital Biotechnology

Modern climate-smart agriculture (CSA) goes beyond genetics by integrating data and digital technologies. Precision biotechnology combines plant science with tools like AI, GPS, sensors, drones, and satellite imaging to track crop and soil conditions in real time, improving efficiency and reducing environmental impact (Syeda, 2025). Digital Twin systems create virtual farm models that help predict stress, optimize resource use, and cut emissions (Awais *et al*., 2025). When paired with biotechnology—such as genomic breeding or RNA-based pest monitoring—controlled environment farming can produce crops with fewer chemical inputs (Ishak *et al*., 2025). Moreover, digital agriculture uses technologies like IoT, robotics, and machine learning to make farming smarter and more sustainable. Advanced systems such as Dynamically Controlled Environment Agriculture (DCEA) further enhance yield stability and energy efficiency, especially in high-tech or indoor farming.

Synthetic Biology and Nanobiotechnology

Synthetic biology aims to modify biological systems or microorganisms to enhance plant growth and nutrient use, while nanobiotechnology uses ultra-small particles to deliver fertilizers or pesticides in precise, controlled amounts. In simple terms, synthetic biology improves the plant's internal processes, whereas nanobiotechnology ensures targeted delivery of inputs. Recent studies indicate that engineered nanomaterials, such as nano-fertilizers and nano-pesticides, can help plants cope with stresses like drought, salinity, and heat by strengthening antioxidant systems and activating stress-response genes (Sabaghnia & Janmohammadi, 2025). Although these technologies are still developing, they are expected to play an important role in future climate-resilient agriculture (Ahmad *et al*., 2024). Research also highlights that combining nanotechnology with genome editing allows nano-carriers to transport CRISPR components directly into plant cells. This approach can accelerate the development of stress-tolerant crops while potentially easing some regulatory and safety challenges (Sahoo *et al*., 2025).

Conclusion and Future Prospects

CSA, enhanced by biotechnology, is now essential for maintaining food security under climate change. Biotechnology enables the development of crops that tolerate heat, drought, flooding, and salinity while using resources efficiently, making farming more resilient. However, technology alone is insufficient—success also requires supportive policies, farmer awareness, financing, and digital tools. Future CSA focuses include improving technology access for smallholders, creating multi-stress tolerant crops through gene editing, using AI for farm decisions, exploring microbiomes and synthetic biology, and strengthening policy and community engagement. Together, these approaches can make agriculture more sustainable and secure for the long term.

Table 1: Some of the biotechnological method contribute to CSA

Crop	Gene/Target	Trait	Improvement	Biotechnological Method
Rice	OsBADH2	Aroma	Increased 2-acetyl-1-pyrroline (2-AP) for enhanced fragrance	CRISPR/Cas9
Rice	Sub1A QTL	Flood tolerance	Enables survival during submergence and flooding	Marker-assisted selection (MAS)
Rice	Saltol	Salinity tolerance	Salinity controls by Na^+ exclusion at seedling stage	MAS
Maize	ZmHDT103	Drought tolerance	Improved water-use efficiency and resilience to water stress	CRISPR/Cas9
Wheat	TaHSP17	Heat tolerance	Enhanced tolerance to high temperatures during growth	CRISPR/Cas9
Barley	SOS1	Salinity tolerance	Improved ability to grow in salty soils	CRISPR/Cas9
Tomato	Multiple stress genes	Drought & salinity tolerance	Increased resilience against combined stresses	CRISPR/Cas9 & MAS
Chickpea	Various multi-omics targets	Drought & salinity tolerance	Improved stress response via proteomics and metabolomics insights	Multi-omics integration (proteomics/ metabolomics)
Millets	NGS-derived markers	Yield & stress tolerance	Rapid development of molecular markers for high-throughput breeding	Next-Generation Sequencing (NGS) & MAS

References

2. Ahmad, Z., Niyazi, S., Firdoos, A., Wang, C., Manzoor, M. A., Ramakrishnan, M., ... & Ding, Y. (2024). Enhancing plant resilience: Nanotech solutions for sustainable agriculture. *Heliyon*, *10*(23).
3. Aijaz, N., Lan, H., Raza, T., Yaqub, M., Iqbal, R., & Pathan, M. S. (2025). Artificial intelligence in agriculture: Advancing crop productivity and sustainability. Journal of Agriculture and Food Research, 20, 101762.
4. Bhattarai, K., Ogden, A. B., Pandey, S., Sandoya, G. V., Shi, A., Nankar, A. N., ... & Dardick, C. (2025). Improvement of crop production in controlled environment agriculture through breeding. *Frontiers in Plant Science*, *15*, 1524601.
5. Chen, J. T. (2025). CRISPR for Climate-Smart and Sustainable Agriculture. 1st ed., Elsevier, Amsterdam, Netherlands. ISBN: 978-0-323-99587-4.
6. Chowdhury, S., Kar, K., Chakraborty, P., Ganguly, S. C., Jit, T., & Majumder, R. (2025). Advanced genetic technologies to improve crop abiotic stress resilience. *Role of Antioxidants in Abiotic Stress Management*, 323-332.

7. Ejaz, M. H., Bilal, M., Habib, U., Attique, M., & Chung, T.-S. (2025). *Crop pest classification using deep learning techniques: A review*. *Journal of Agricultural Informatics*, 12(3), 45–60.
8. Ferrão, M. A. G., Da Fonseca, A. F., Volpi, P. S., de Souza, L. C., Comério, M., Filho, A. C. V., ... & Ferrão, L. F. V. (2024). Genomic-assisted breeding for climate-smart coffee. *The Plant Genome*, *17*(1), e20321.
9. Gatica-Arias, A., & Hernández-Soto, A. (2025). New Plant Breeding Technologies for Climate-Smart Agriculture: Enhancing Abiotic Stress Tolerance. In *Plant Breeding 2050: Next-Gen Crops* (pp. 541-567). Singapore: Springer Nature Singapore.
10. Ishak, F. N., Abd Hadi, N., Kassim, R., Mohamad, M., & Che Othman, M. H. (2025). Controlled environment agriculture for vegetable and fruit production in Malaysia: technological adaptations and innovations in biological and biotechnological approaches. *The Journal of Horticultural Science and Biotechnology*, 1–20.
11. Jain, S. M., Brar, D. S., & Ahloowalia, B. S. (Eds.). (2009). Molecular techniques in crop improvement (pp. 1–372). Springer.
12. Khalid, B., Javed, M. U., Ikram, M., Ateeq, M., Ashraf, M. A., Riaz, T., ... & Maqbool, R. (2026). Precision Rewiring of Stress-Responsive Gene Networks Via CRISPR: Mechanistic Pathways Toward Climate-Smart Agriculture. *Journal of Crop Health*, *78*(1), 2.
13. Krishna, A., T. P., Maharajan, T., & Ceasar, S. A. (2022). Improvement of millets in the post-genomic era. *Physiology and molecular biology of plants: an international journal of functional plant biology*, *28*(3), 669–685.
14. Mmbando, G. S. (2025). Exploring the Capacity of Modern Biotechnology to Enhance Climate-Smart Crop Production in Africa. *Discover Agriculture*, 1(3), Article 27.
15. Neumeier, J., & Meister, G. (2021). siRNA specificity: RNAi mechanisms and strategies to reduce off-target effects. Frontiers in Plant Science, 11, 526455
16. Ngongolo, K., & Mmbando, G. S. (2024). The recent genetic modification techniques for improving soil conservation, nutrient uptake and utilization. *GM Crops & Food*, *15*(1), 233–247.
17. Pereponova, A., Grahmann, K., Lischeid, G., Bellingrath-Kimura, S. D., & Ewert, F. (2023). *Sustainable transformation of agriculture requires landscape experiments*. Heliyon, 9(11), e21215.
18. Rajput, M., Kumari, P., & Sharma, V. (2021). RNA interference and CRISPR/Cas gene editing for crop improvement. *Plants*, 10(9), 1914.
19. Rao, Y., Yang, X., Pan, C., Wang, C., & Wang, K. (2022). Advance of clustered regularly interspaced short palindromic repeats-Cas9 system and its application in crop improvement. *Frontiers in plant science*, *13*, 839001.
20. Rautela, I., Chaurasiya, D. K., Singh, S., *et al*. (2026). Harnessing Omics Technologies to Mitigate Drought Stress in Crop Plants. *Journal of Agronomy and Crop Science*, 212(1), 33–54.
21. Sabaghnia, N., & Janmohammadi, M. (2025). Nanotechnology for Plant Stress Tolerance under Climate Change.
22. Sahoo, D., Swapna, D., Mohanty, A., Sethi, B., Samal, P. P., Mohapatra, A., & Sahoo, J. P. (2025). Nanobiotechnology Approaches for Climate Change Adaptation in Crops. In *Plant Biotechnology and Food Security* (pp. 221-238). CRC Press.
23. Saurabh, S., Vidyarthi, A. S., & Prasad, D. (2014). RNA interference: Concept to reality in crop improvement. *Planta*, 239(3), 543–564.
24. Shan Q, Zhang Y, Chen K, Zhang K, Gao C. Creation of fragrant rice by targeted knockout of the OsBADH2 gene using TALEN technology. Plant Biotechnol J. 2015 Aug;13(6):791-800.
25. Syeda, A. (2025). Harnessing Multi-Omics and Genome-Editing Technologies for Climate-Resilient Agriculture: Bridging AI-Driven Insights with Sustainable Crop Improvement. *Plant Molecular Biology*, 108(4–5), 389–408. Springer Nature.

26. Wambi, W., Otienno, G., Tumwesigye, W., & Mulumba, J. (2021). Genetic and genomic resources for finger millet improvement: opportunities for advancing climate-smart agriculture. *Journal of Crop Improvement*, *35*(2), 204-233.
27. Wang J, Huang C, Tang L, Chen H, Chen P, Chen D, Wang D. (2025). Identification of Submergence Tolerance Loci in Dongxiang Wild Rice (DXWR) by Genetic Linkage and Transcriptome Analyses. Int J Mol Sci ;26(5):1829.
28. Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H., & Ao, X. (2024). Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy*, *14*(7), 1360.
29. Zotti, M., Dos Santos, E. A., Cagliari, D., Christiaens, O., Taning, C. N. T., & Smagghe, G. (2018). RNA interference technology in crop protection against arthropod pests, pathogens and nematodes. *Pest management science*, *74*(6), 1239-1250.