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Smart Seeds: AI and Gene Editing Join Forces to Grow Climate-Resilient Crops

*G Aishwarya and Soubhagya Behera

Department of Seed Science and Technology, College of Agriculture,
OUAT, Bhubaneswar, Odisha, India- 751003

*Corresponding Author's email: aishwaryagummakonda88@gmail.com

Climate change poses severe threats to global food security due to increased temperatures, unpredictable rainfall patterns, and higher incidences of drought, salinity, and heat stress. Traditional breeding alone is too slow to develop resilient crop varieties capable of adapting to these rapid environmental changes. Smart seeds represent a transformative solution by integrating gene editing technologies with artificial intelligence (AI) and high-throughput phenomics/genomics tools to accelerate the development of climate-resilient crops. It explores how modern genome editing tools — including CRISPR/Cas9, base editors, and prime editors — alongside AI-driven prediction and selection methods, create a new frontier in crop improvement.

Keywords: Smart seeds; Climate-resilient crops; Gene editing; CRISPR/Cas9; Base editing; Prime editing; Artificial Intelligence (AI); Machine learning; Digital breeding; Abiotic stress tolerance; Drought resistance; Salinity tolerance; Heat stress tolerance; Genome engineering; Precision breeding; Sustainable agriculture; Food security; Phenomics; Genomic selection; Transgene-free crops.

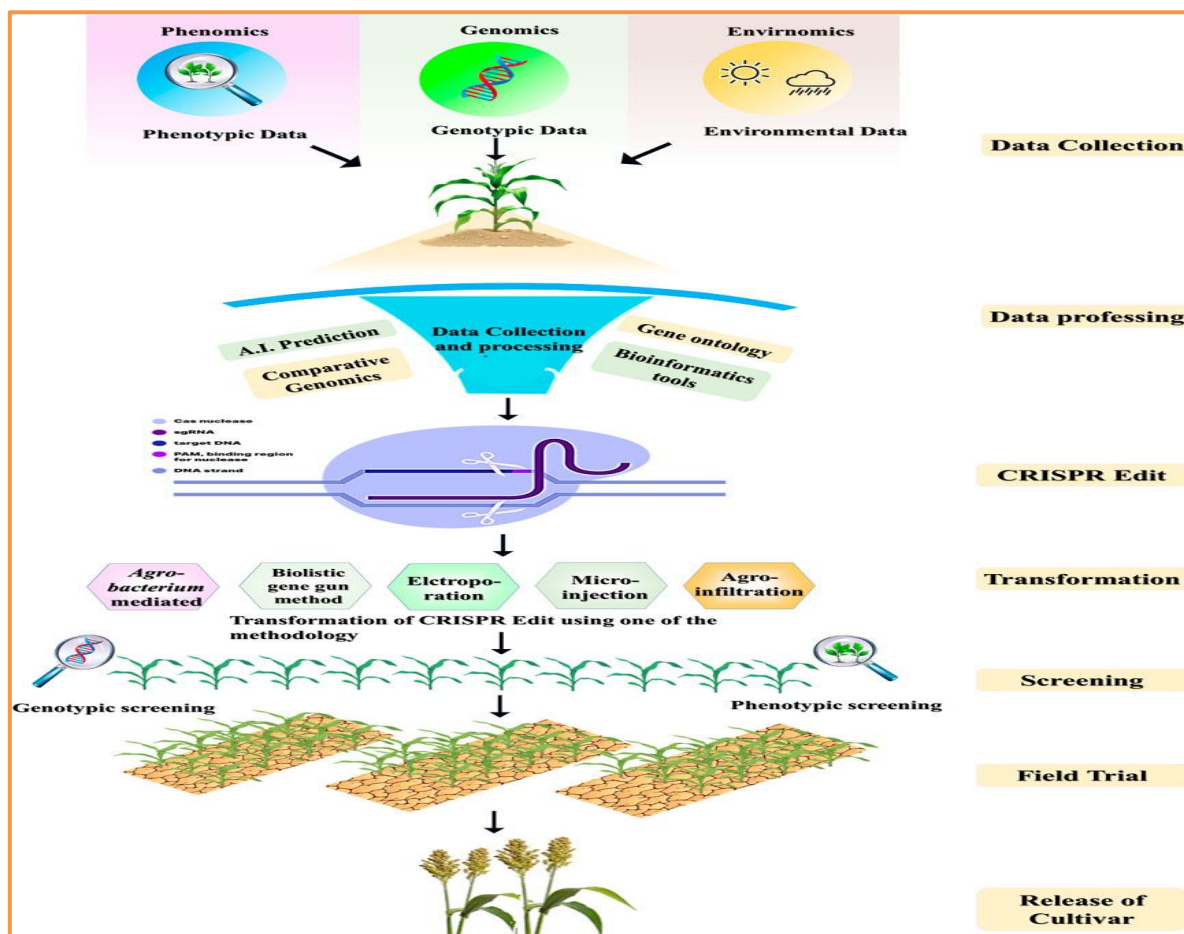
Introduction

Agricultural systems worldwide are experiencing unprecedented stress due to climate change. Increased atmospheric temperatures and extreme weather patterns threaten crop productivity, soil health, and food security. These stressors are particularly harmful because they disrupt plant physiological and metabolic processes, reduce yields, and exacerbate pest and disease outbreaks. Traditional breeding has contributed immensely to agricultural productivity, but its slow pace cannot meet the urgent need for climate-smart crop development. In response, gene editing technologies provide precise and efficient tools to manipulate plant genomes and enhance traits related to stress tolerance, yield stability, and resource use efficiency. When coupled with AI and machine learning (ML), these tools enable data-driven decision making that significantly accelerates breeding cycles and improves trait selection accuracy.

Gene Editing Technologies In Climate Resilience

CRISPR/Cas9

The CRISPR/Cas9 system has transformed plant breeding through its precision, efficiency, and ease of design. It employs a guide RNA (gRNA) to direct the Cas9 endonuclease to a specific DNA sequence, generating a targeted double-strand break (DSB). The break is repaired by the plant's natural DNA repair pathways—non-homologous end joining (NHEJ) or homology-directed repair (HDR)—resulting in precise genetic modifications. This technology has been applied to improve disease resistance, nutritional quality, hybrid seed production, and tolerance to drought, salinity, and heat stress. By enabling targeted manipulation of key genes, CRISPR/Cas9 accelerates crop improvement for climate resilience. However, concerns regarding off-target effects, delivery efficiency, and regulatory variability require continued research and refinement.



Base Editing

Base editors are advanced CRISPR/Cas9-derived tools that enable precise single-nucleotide substitutions without creating double-strand breaks or requiring donor DNA templates. They function by combining a modified Cas9 protein with deaminase enzymes to directly convert cytosine to thymine (C→T) or adenine to guanine (A→G). Cytosine base editors (CBEs) and adenine base editors (ABEs) thus facilitate predictable and targeted genetic changes with reduced unintended mutations. This approach enhances editing accuracy and genomic stability compared to conventional CRISPR systems. Base editors have shown high efficiency in major crops such as rice and soybean. They have been successfully applied to improve traits like salinity tolerance, supporting the development of climate-resilient crop varieties.

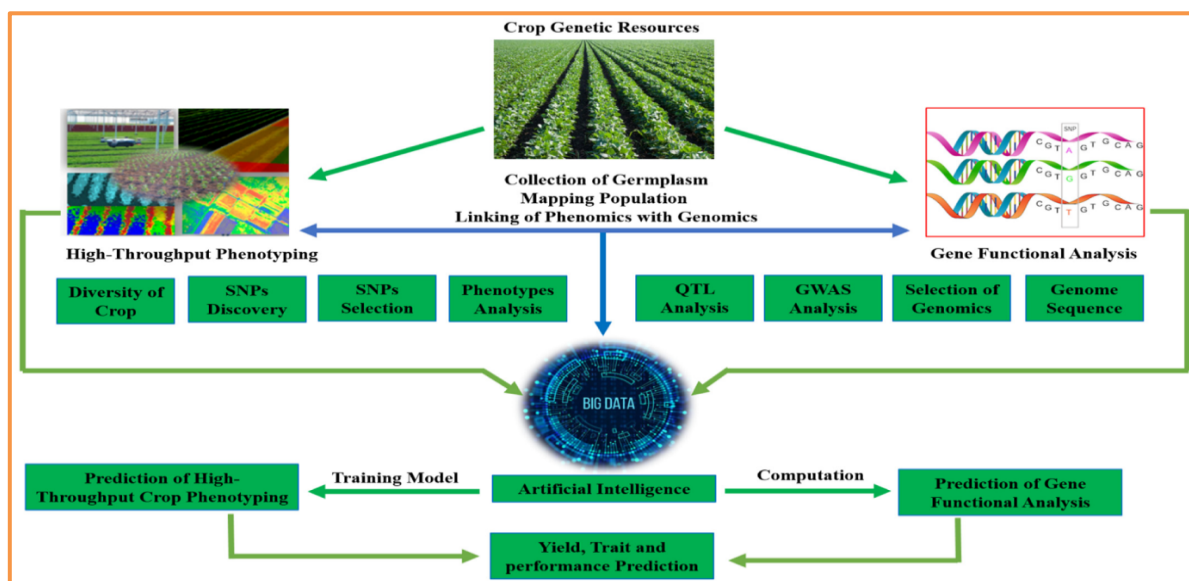
Prime Editing

Prime editing is a versatile and precise genome-editing technology that enables targeted insertions, deletions, and base substitutions without generating double-strand breaks. It integrates a modified Cas9 nickase with a reverse transcriptase and employs a prime editing guide RNA (pegRNA) to both target the DNA sequence and encode the intended modification. This method broadens the scope of possible genetic edits while minimizing unintended mutations and off-target effects. Prime editing has shown strong potential in crop improvement by enhancing yield, disease resistance, and tolerance to abiotic stresses. Consequently, it represents a promising approach for developing climate-resilient and next-generation smart seed varieties.

Ai Integration in Smart Seed Development

The integration of artificial intelligence (AI) and machine learning into smart seed development significantly enhances the precision, speed, and efficiency of gene editing and breeding programs. AI platforms analyse large and complex datasets from genomics, phenomics, and environmental sources to identify optimal gene targets. They enable predictive modelling of gene–trait associations and optimize guide RNA (gRNA) design to

minimize off-target effects. Additionally, AI supports genomic selection and accurate trait prediction across diverse environments. Advanced algorithms such as Deep Neural Networks (DNNs) and Random Forests (RF) improve pattern recognition and selection accuracy. Collectively, these technologies form the foundation of digital breeding systems that accelerate the development of climate-resilient, high-performing crop varieties.



Target Genes for Climate Resilience

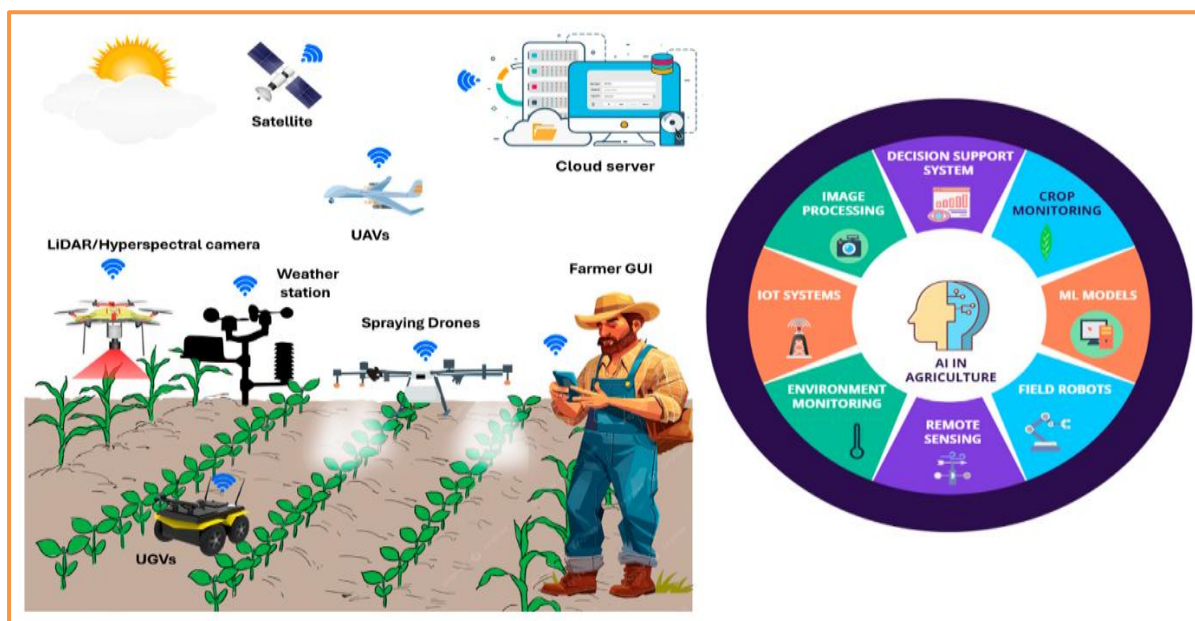
Gene editing strategies for climate resilience primarily target key regulatory genes involved in plant stress-response pathways. Positive regulators, such as *ERECTA* and specific transcription factors, enhance tolerance by improving root architecture, water-use efficiency, and cellular protection mechanisms, thereby strengthening the plant's ability to withstand environmental stress. Conversely, negative regulators that restrict growth or stress adaptation can be silenced or modified to remove constraints under adverse conditions. By precisely editing these genes, crops can maintain yield stability and physiological performance under drought, heat, and salinity stress, making gene-targeted interventions a crucial approach for developing climate-resilient agricultural systems.

Challenges and Regulatory Considerations

Gene editing, despite its transformative promise, faces significant scientific and regulatory constraints that affect large-scale deployment. Off-target effects remain a major biosafety concern, as unintended genomic alterations may disrupt gene function. Efficient delivery of editing components into diverse crop species, particularly those with complex genomes, is technically challenging and species-specific. Regulatory approaches vary globally, with some countries treating gene-edited crops as GMOs, while others differentiate based on the presence of foreign DNA. Public acceptance depends on transparent communication about safety and oversight. Transgene-free edits, especially under SDN1 and SDN2 categories, often receive more favourable regulatory treatment, potentially accelerating commercialization.

Implications for Food Security and Sustainable Agriculture

AI-guided gene editing enables the development of climate-resilient crops that sustain productivity under environmental stress. Smart seeds enhance yield stability, nutritional quality, stress tolerance, and resource-use efficiency across diverse agroecological conditions. Integration with genomic selection and digital phenotyping strengthens precision breeding and expands the use of genetic diversity. This combined approach improves adaptability to changing climates while maintaining high agricultural productivity. It supports sustainable farming systems by reducing vulnerability to climate variability. Ultimately, these innovations contribute directly to long-term food security for a growing global population.



Conclusion

The synergy of gene editing technologies and AI-based tools has opened a transformative path in crop improvement. Smart seeds embody the next generation of agricultural innovation, capable of addressing climate change challenges by enhancing crop resilience and productivity. For seed scientists and technologists, mastering these tools is essential for future research and breeding programs that safeguard global food systems.

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