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CRISPR Based Crop Improvement for Sustainable Agriculture Recent Advances Challenges and Future Perspectives

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Abstract: -

Global agriculture is facing unprecedented challenges due to climate change, population growth, diminishing natural resources, and the increasing incidence of pests and diseases. These challenges demand innovative breeding approaches capable of developing high yielding, climate-resilient, and nutritionally improved crop varieties within shorter timeframes. Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated (Cas) proteins have emerged as transformative genome-editing tools that enable precise, efficient, and targeted modification of plant genomes. Unlike conventional breeding, which often requires several generations to introduce desirable traits, CRISPR technology allows breeders to directly modify genes associated with yield, stress tolerance, disease resistance, nutritional quality, and adaptation to changing environments. The application of CRISPR has been demonstrated successfully in several economically important crops, including rice, wheat, maize, soybean, tomato, potato, and cotton. Recent advances such as base editing, prime editing, multiplex genome editing, and DNA free genome editing have further expanded the scope of crop improvement while reducing unintended genetic changes. These technologies have accelerated the development of crop varieties capable of addressing food security and environmental sustainability. Despite its remarkable potential, several challenges remain, including efficient delivery systems, regulatory uncertainty, public acceptance, intellectual property concerns, and the possibility of off target mutations. Continued research, transparent regulation, and responsible implementation will be essential to maximize the benefits of CRISPR technology.

This article summarizes the principles of CRISPR-based genome editing, highlights its major applications in sustainable crop improvement, discusses current challenges, and outlines future opportunities for integrating CRISPR with genomics, artificial intelligence, and precision breeding to strengthen global food security.

Keywords: CRISPR/Cas9, Genome Editing, Sustainable Agriculture, Plant Breeding, Crop Improvement; Climate Resilient Crops.

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1. Introduction:

Agriculture has always been the foundation of human civilization, providing food, nutrition, livelihoods, and raw materials for growing populations. Today, however, agricultural production faces mounting pressure from rapid population growth, climate variability, land degradation, water scarcity, and the emergence of new pests and pathogens. According to projections by international organizations, global food production must increase substantially by 2050 to meet the nutritional demands of an expanding population while minimizing environmental impacts. Achieving this balance requires crop improvement strategies that are not only effective but also sustainable. For decades, conventional plant breeding has played a central role in increasing crop productivity through selection, hybridization, and mutation breeding. These methods have produced many successful cultivars but are often limited by long breeding cycles, dependence on naturally occurring genetic variation, and the difficulty of improving complex traits controlled by multiple genes. Although marker-assisted selection and genomic selection have accelerated breeding programs, the need for more precise and efficient technologies remains significant. Genome editing has transformed modern plant breeding by enabling targeted modifications of specific genes without altering the remainder of the genome. Among the available genome-editing technologies, CRISPR has become the most widely adopted because of its simplicity, versatility, high editing efficiency, and comparatively low cost. Adapted from the natural immune system of bacteria and archaea, the CRISPR-Cas system uses a guide RNA to direct the Cas enzyme to a selected DNA sequence, where precise genetic modifications can be introduced. This level of precision allows plant breeders to improve important agronomic traits while preserving the desirable genetic background of elite cultivars.

During the past decade, CRISPR technology has moved rapidly from laboratory research to practical applications in agriculture. Researchers have successfully edited genes associated with grain yield, flowering time, plant architecture, nutrient-use efficiency, resistance to fungal, bacterial, and viral diseases, tolerance to drought and salinity, and enhanced nutritional quality. In rice, targeted editing of yield- and stress-related genes has improved productivity under adverse environmental conditions. In wheat, CRISPR has been used to enhance resistance to fungal diseases and improve grain quality. Similar progress has been reported in maize, soybean, tomato, potato, and several horticultural crops, highlighting the broad applicability of this technology across diverse plant species. The emergence of advanced genome-editing approaches, including base editing and prime editing, has further increased the precision of genetic modifications by enabling single-nucleotide substitutions or targeted sequence changes without creating double-stranded DNA breaks. These innovations reduce the likelihood of unintended genetic alterations and expand the range of traits that can be improved through genome editing. At the same time, integrating CRISPR with genomic selection, speed breeding, high-throughput phenotyping, and artificial intelligence is creating new opportunities for accelerating genetic gain in crop improvement programs.

Although CRISPR technology offers tremendous promise, its widespread adoption depends on addressing technical, regulatory, ethical, and societal challenges. Efficient delivery methods, comprehensive biosafety assessments, harmonized regulatory frameworks, and public awareness will be critical for ensuring the responsible use of genome-edited crops. As scientific knowledge and regulatory policies continue to evolve, CRISPR-based breeding is expected to become a cornerstone of sustainable agriculture, contributing to resilient cropping systems, improved resource-use efficiency, and long-term food and nutritional security.

This article examines recent advances in CRISPR-based crop improvement, explores its contributions to sustainable agriculture, discusses current limitations, and highlights future research directions for developing resilient and productive crop varieties capable of meeting global agricultural challenges.

2. CRISPR Technology: Principles and Mechanism of Genome Editing

The development of CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology has revolutionized plant breeding by providing a fast, accurate, and cost-effective method for modifying plant genomes. Originally discovered as a natural adaptive immune system in bacteria and archaea, CRISPR enables these microorganisms to recognize and destroy invading viruses. Scientists adapted this natural defense mechanism into a powerful genome-editing tool capable of introducing precise genetic changes in plants, animals, and microorganisms. The CRISPR-Cas system functions through two key components: a guide RNA (gRNA) and a CRISPR associated (Cas) protein. The guide RNA is designed to recognize a specific DNA sequence within the plant genome, while the Cas protein acts as molecular scissors that cut the DNA at the targeted location. Once the DNA is cleaved, the plant's natural repair mechanisms become active. During this repair process, small insertions, deletions, or precise sequence modifications can be introduced, allowing researchers to knock out undesirable genes, modify existing genes, or insert beneficial genetic changes. Among the different CRISPR systems, CRISPR-Cas9 remains the most widely used because of its high editing efficiency and ease of design. Cas9 has been successfully employed in numerous crop species, including rice, wheat, maize, soybean, tomato, and cotton, to improve yield, disease resistance, stress tolerance, and grain quality. Its versatility has made it the preferred genome-editing platform in many crop improvement programs.

Recent years have witnessed the development of several advanced CRISPR systems that extend the capabilities of genome editing. Cas12 (Cpf1) differs from Cas9 in its DNA recognition pattern and produces staggered DNA cuts, making it particularly useful for editing specific genomic regions. Cas13 targets RNA rather than DNA, providing new opportunities for controlling RNA viruses and regulating gene expression without permanently altering the genome. These innovations have significantly expanded the applications of CRISPR in agricultural research.

Another important breakthrough is the development of base editing, which enables scientists to change a single DNA base without generating double-stranded DNA breaks. This approach is especially valuable for correcting naturally occurring mutations or introducing beneficial alleles responsible for improved agronomic traits. Base editing minimizes unwanted genetic alterations and enhances editing precision, making it an attractive strategy for modern plant breeding.An equally promising advancement is prime editing, often described as a "search-and-replace" genome-editing technology. Prime editing combines a modified Cas protein with reverse transcriptase and a specially designed guide RNA to introduce targeted insertions, deletions, or substitutions without requiring donor DNA templates. This technology offers greater flexibility and accuracy than conventional CRISPR approaches and has enormous potential for improving complex traits controlled by multiple genes. Modern breeding programs are also utilizing multiplex genome editing, where multiple genes are edited simultaneously within a single experiment. Since many important agricultural traits such as drought tolerance, yield potential, nutrient-use efficiency, and disease resistance are governed by several interacting genes, multiplex editing allows breeders to improve these complex traits more efficiently than traditional breeding methods.

Delivering CRISPR components into plant cells remains a critical step in successful genome editing. Common delivery methods include *Agrobacterium tumefaciens*-mediated transformation, particle bombardment (gene gun), polyethylene glycol-mediated transformation of protoplasts, and ribonucleoprotein (RNP)-based delivery. More recently, DNA - free genome editing using CRISPR ribonucleoproteins has gained attention because it avoids stable integration of foreign DNA into the plant genome. This approach may simplify regulatory approval in several countries and improve public acceptance of genome-edited crops. Compared with conventional breeding and earlier

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3. APPLICATIONS OF CRISPR IN CROP IMPROVEMENT

CRISPR-based genome editing has been successfully applied in a wide range of crop species to enhance yield, improve resistance to biotic and abiotic stresses, and enhance nutritional quality. The technology enables precise modifications in native elite varieties without introducing foreign DNA, thus retaining their agronomic adaptability and consumer acceptability.

3.1 Yield and Agronomic Trait Improvement

Genes controlling plant architecture, tillering, panicle size, and grain number have been targeted to increase yield potential. For example, editing of *OsSPL14* and *IPA1* in rice produced ideal plant architecture with higher grain yield under field conditions (Wang et al., 2021). In wheat, *TaGW2* deletion improved thousand-grain weight and yield (Zhang et al., 2022). CRISPR-mediated editing of *GmARGOS8* in soybean resulted in increased yield by modulating auxin signaling (Lu et al., 2020).

3.2 Disease Resistance

CRISPR has been widely used to develop disease-resistant crops by targeting susceptibility (S) genes or enhancing defense responses. For instance, editing of *MLO* genes in wheat, tomato, barley, and rice confers broad-spectrum resistance to powdery mildew (Wang et al., 2014; Jia et al., 2020). Editing of *eIF4E* in rice and banana imparted resistance to Rice dwarf virus and Banana bunchy top virus, respectively (Zhang et al., 2016; Tripathi et al., 2019).

3.3 Abiotic Stress Tolerance

CRISPR-edited crops with improved tolerance to drought, salinity, heat, and cold stresses have been reported. In rice, editing of *OsDREB1A* and *SNAC1* enhanced drought tolerance (Ma et al., 2019). In tomato, editing of *SlMAPK3* improved tolerance to water deficit (Zsögön et al., 2018). Overexpression of *TaNAC69* in wheat via CRISPR activation increased tolerance to drought and salinity (Sánchez-León et al., 2018).

3.4 Nutritional Quality Improvement

Genome editing has been used to improve nutrient content and food quality. In rice, editing of *OsNR2* and *OsSBEI* increased grain iron and amylose content, respectively (Zhang et al., 2020; Lin et al., 2020). High-oleic and low-linolenic acid soybean lines were developed by editing *FAD2-1A* and *FAD3A* genes (Haun et al., 2014). CRISPR editing in tomato increased the content of γ-aminobutyric acid (GABA) by targeting *SlGAD2* gene (Nonaka et al., 2021).

Figure 1. CRISPR/Cas9 Genome Editing Mechanism in Plants

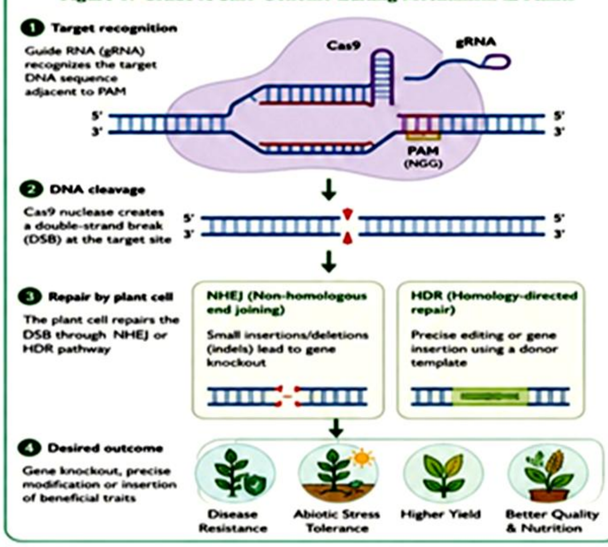

Table 1. Examples of CRISPR/Cas-Mediated Gene Editing and Trait Improvement in Major Crops

Crop	Target Gene	Editing Type	Trait Improved	Key Outcome	Reference
Rice (*Oryza sativa*)	*OsSPL14*	Gene knockout	Plant architecture, yield	Increased grain yield by 20–30%	Wang et al., 2021
	OsIPA1	Gene knockout	Panicle size, yield	More spikelets and higher yield	Jiao et al., 2020
	OsMLO5	Gene knockout	Powdery mildew resistance	Broad-spectrum disease resistance	Nishimasu et al., 2018
	OsNR2	Gene knockout	Grain iron content	Higher iron accumulation in grains	Zhang et al., 2020
	OsSBEI	Gene knockout	Amylose content	Improved eating and cooking quality	Lin et al., 2020
Wheat (*Triticum aestivum*)	*TaGW2*	Gene knockout	Grain size, yield	Increased thousand-grain weight	Zhang et al., 2022
	TaMLO-A1	Gene knockout	Powdery mildew resistance	Enhanced resistance	Wang et al., 2014
	TaLr46	Gene editing	Leaf rust resistance	Improved resistance to leaf rust	Wang et al., 2020
	TaNAC69	CRISPR activation	Drought & salt tolerance	Better tolerance to abiotic stresses	Sánchez-León et al., 2018
Maize (*Zea mays*)	*ZmARGOS8*	Gene knockout	Plant architecture, yield	Improved yield under field conditions	Wang et al., 2019
	ZmPDS	Gene knockout	Herbicide tolerance	Albinism; selection marker	Char et al., 2017
	ZmGL13.1	Gene knockout	Disease resistance	Enhanced resistance to anthracnose	Jiang et al., 2018
Soybean (*Glycine max*)	*GmARGOS8*	Gene knockout	Yield	Increased seed yield	Lu et al., 2020
	GmFAD2-1A	Gene knockout	Oil quality (high oleic)	Increased oleic acid content	Haun et al., 2014
	GmFAD3A	Gene knockout	Oil quality (low linolenic acid)	Improved oil stability	Haun et al., 2014
Tomato (*Solanum lycopersicum*)	*SlMLO1*	Gene knockout	Powdery mildew resistance	Disease-resistant plants	Jia et al., 2020
	SlMAPK3	Gene knockout	Drought tolerance	Improved water use efficiency	Zsögön et al., 2018
	SlGAD2	Gene knockout	Nutritional quality (GABA)	Increased GABA content	Nonaka et al., 2021
Potato (*Solanum tuberosum*)	*StALS*	Gene knockout	Herbicide tolerance	Enhanced tolerance to ALS inhibitors	Kim et al., 2018
	StPDS	Gene knockout	Selection marker	Albino phenotype for selection	Clasen et al., 2016
Cotton (*Gossypium hirsutum*)	*GhCLA1*	Gene knockout	Fiber quality	Improved fiber quality	Li et al., 2020
	GhPDF2.1	Gene knockout	Verticillium wilt resistance	Enhanced disease resistance	Sun et al., 2020
Chickpea (*Cicer arietinum*)	*CaMLO1*	Gene knockout	Powdery mildew resistance	Improved disease resistance	Bhowmik et al., 2021
	CaNRT1.1	Gene editing	Nitrogen use efficiency	Better nitrogen utilization	Sharma et al., 2022

Key Impact of CRISPR in Sustainable Agriculture

- ✔ Improves yield and resource use efficiency
- ✔ Enhances resistance to diseases and climatic stresses
- ✔ Enhances nutritional value and food quality
- ✔ Reduces dependence on chemical pesticides and fertilizers
- ✔ Supports climate-resilient and sustainable cropping systems

Figure 2. CRISPR Applications for Sustainable Agriculture

genome-editing technologies such as zinc finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs), CRISPR offers several distinct advantages. It is relatively inexpensive, easy to design, highly efficient, and capable of editing multiple genes simultaneously. These characteristics have accelerated crop improvement programs worldwide and enabled researchers to address agricultural challenges that were previously difficult to solve. As genome editing technologies continue to evolve, CRISPR is increasingly being integrated with genomics, transcriptomics, high throughput phenotyping, artificial intelligence, and speed breeding. This multidisciplinary approach is expected to shorten breeding cycles, improve selection accuracy, and facilitate the development of climate-resilient, high yielding, and nutritionally superior crop varieties. Consequently, CRISPR has become one of the most influential innovations in contemporary plant breeding and is poised to play a central role in achieving sustainable agricultural production in the coming decades. Figure :1

3. Applications of CRISPR in Crop Improvement for Sustainable Agriculture

In India, application of CRISPR technology has transformed crop improvement by enabling plant breeders to modify genes associated with economically important traits with remarkable precision. Unlike conventional breeding, where the transfer of desirable traits may require several generations and often introduces unwanted genetic material, CRISPR allows targeted editing of specific genes while preserving the superior genetic background of elite cultivars. Consequently, genome editing has become an indispensable tool for developing climate-resilient, high-yielding, disease-resistant, and nutritionally enhanced crop varieties that support sustainable agricultural production.

3.1 Yield Enhancement and Agronomic Improvement

Increasing crop productivity remains one of the primary objectives of plant breeding. CRISPR technology has enabled researchers to manipulate genes regulating plant architecture, flowering time, tillering, grain size, seed weight, and biomass production.

In rice (*Oryza sativa*), targeted editing of OsSPL14, IPA1, and Gn1(Table 1) has significantly improved grain number, panicle architecture, and overall yield potential. Similarly, knockout of the TaGW2 gene in wheat resulted in larger grain size and higher thousand-grain weight. In maize and soybean, editing genes associated with plant growth and carbon allocation has contributed to increased biomass accumulation and improved harvest index. These improvements demonstrate that genome editing can substantially accelerate genetic gain while reducing the breeding cycle, making it an effective strategy for meeting future food demands.

India has begun advancing CRISPR edited crops, but very few have been officially released for commercial cultivation.

3.2 Development of Disease Resistant Crops

Plant diseases account for considerable annual losses in global agricultural production. CRISPR has emerged as a sustainable alternative to excessive pesticide use by enabling precise modification of disease susceptibility genes and enhancement of natural plant defence mechanisms. One of the

Table :1 List of CRISPR developed varieties remain in research, confined field trials, or are awaiting regulatory approval.

Crop	Variety/Line	Target Trait	Institution	Status
Rice (*Oryza sativa*)	Improved Samba Mahsuri, Pusa Basmati (edited lines)	Bacterial blight resistance, yield, grain quality	IIRR-Indian Institute of Rice Research, Hyderabad	Experimental
Rice	CRISPR-edited drought-tolerant rice	Drought tolerance	IIRR- Indian Institute of Rice Research	Field evaluation
Tomato (*Solanum lycopersicum*)	CRISPR tomato lines	Shelf life, fruit quality	IIVR-Indian Institute of Vegetable Research, Varanasi (U.P)	Research stage
Banana (*Musa spp.*)	CRISPR banana	Fusarium wilt resistance	NRCB-National Research Centre for Banana, Trichy, (Tiruchirappalli) TN.	Experimental
Wheat (*Triticum aestivum*)	CRISPR wheat lines	Rust resistance, grain quality	IIWBR-Indian Institute of Wheat and Barley Research, Karnal, (HR)	Research stage
Mustard (*Brassica juncea*)	Edited mustard	Improved oil quality	IARI-Indian Agricultural Research Institute, New Delhi	Research stage
Chickpea (*Cicer arietinum*)	CRISPR chickpea	Drought tolerance, disease resistance	IIPR-Indian Institute of Pulses Research, Kanpur (U.P.)	Research stage

Source: https://www.icar.gov.in/en/recent-research-initiatives?utm most successful examples involves the MLO gene, where gene knockout has conferred durable resistance to powdery mildew in wheat, barley, tomato, and several other crops. Likewise, editing the eIF4E gene has generated resistance against important viral diseases in rice, cucumber, cassava, and banana. CRISPR has also been employed to improve resistance against bacterial blight, bacterial leaf streak, blast disease, and fungal pathogens by modifying host-pathogen interaction pathways.

Such disease resistant varieties reduce dependence on chemical fungicides and insecticides, thereby lowering production costs while minimizing environmental contamination.

3.3 Improving Tolerance to Abiotic Stresses

Climate change has intensified the occurrence of drought, salinity, heat, cold, and flooding, threatening agricultural productivity worldwide. CRISPR-based genome editing offers a rapid approach for developing stress-resilient crop varieties capable of maintaining productivity under adverse environmental conditions.

Editing drought-responsive genes such as OsDREB1A, SNAC1, and AREB has enhanced water-use efficiency and drought tolerance in rice. In tomato, modification of SlMAPK3 improved tolerance to water deficit, while editing stress-responsive genes in soybean increased resistance to salinity. Similar improvements have been reported in maize and wheat, where edited plants exhibited enhanced antioxidant activity, better root development, and improved physiological adaptation under environmental stress. The development of climate resilient cultivars through genome editing contributes directly to sustainable agricultural systems by ensuring stable crop production despite increasingly unpredictable climatic conditions.

3.4 Nutritional Quality Improvement

Beyond increasing productivity, modern breeding aims to improve the nutritional value of staple food crops. CRISPR technology provides a precise method for enhancing essential nutrients while maintaining desirable agronomic characteristics.

Researchers have successfully increased iron and zinc accumulation in rice by editing nutrient transport genes. Similarly, modification of starch biosynthesis genes has improved cooking quality and grain texture. In soybean, editing the FAD2 gene increased oleic acid content while reducing undesirable polyunsaturated fatty acids, thereby improving oil stability and nutritional value. In tomato, CRISPR mediated modification of the SlGAD2 gene enhanced gamma-aminobutyric acid (GABA) concentration, producing fruits with added health benefits.

These examples illustrate how genome editing can simultaneously address food security and nutritional security, supporting the development of healthier diets without compromising agricultural productivity.

3.5 Sustainable Weed and Pest Management

CRISPR has also opened new opportunities for integrated pest and weed management. Researchers are exploring genome editing to improve herbicide tolerance, insect resistance, and pest management strategies while reducing reliance on synthetic agrochemicals.

- Enhances yield potential and resource-use efficiency.
- Improves resistance to insects, fungi, bacteria, and viruses.
- Develops crops tolerant to drought, salinity, heat, and other climate-related stresses.
- Improves nutritional quality and food safety.
- Reduces dependence on pesticides, fertilizers, and other agrochemicals.
- Supports environmentally sustainable and climate-smart agricultural systems.

Table 2. Representative Applications of CRISPR in Major Crop Species

Crop	Target Gene	Trait Improved	Major Outcome
Rice	OsSPL14	Grain yield	Improved panicle architecture and yield
Rice	OsNR2	Nitrogen use efficiency	Reduced fertilizer requirement
Wheat	TaGW2	Grain size	Increased thousand-grain weight
Wheat	MLO	Powdery mildew resistance	Durable disease resistance
Maize	ARGOS8	Drought tolerance	Improved productivity under water deficit
Soybean	FAD2	Oil quality	Increased oleic acid content
Tomato	SlMAPK3	Drought tolerance	Better water-use efficiency
Tomato	SlGAD2	Nutritional quality	Enhanced GABA concentration
Potato	ALS	Herbicide tolerance	Improved weed management
Cotton	GhCLA1	Fibre quality	Enhanced fibre characteristics

Key Contributions of CRISPR to Sustainable Agriculture

- Accelerates crop improvement by reducing breeding time.
- Enables precise modification of elite cultivars without introducing undesirable traits.

Overall, CRISPR-based genome editing represents a paradigm shift in plant breeding. By integrating precision genetics with conventional breeding strategies, researchers can develop crop varieties that are more productive, resilient, and environmentally sustainable. As new genome-editing technologies continue to evolve, CRISPR is expected to play an increasingly important role in ensuring global food and nutritional security under changing climatic conditions.

CRISPR-edited crop approved in India

As of 2026, India has not officially released a CRISPR-edited crop variety for large-scale commercial cultivation under the national variety release system. However:

- In 2022, the Government of India exempted certain SDN-1 and SDN-2 genome-edited plants (those without foreign DNA insertion) from parts of the GMO regulatory framework, making research and commercialization pathways easier.
- Several ICAR institutes, agricultural universities, and biotechnology organizations are conducting advanced field evaluations of CRISPR-edited rice, wheat, tomato, banana, chickpea, mustard, and other crops.
- Commercial releases are expected in the coming years as candidates' complete biosafety and varietal evaluation requirements.

4. Challenges, Biosafety, Regulatory Framework, and Future Perspectives

Although CRISPR technology has revolutionized plant breeding by enabling precise and efficient genome editing, several scientific, technical, regulatory, and social challenges continue to influence its widespread adoption. Addressing these issues is essential for translating laboratory discoveries into commercially successful crop varieties that contribute to sustainable agriculture and global food security.

4.1 Technical Challenges in CRISPR-Based Crop Improvement

Despite remarkable progress, genome editing is not free from limitations. One of the primary concerns is off-target editing, where unintended DNA sequences may be modified due to partial similarity with the designed guide RNA. Although the frequency of off-target mutations has been significantly reduced through improved guide RNA design, high-fidelity Cas proteins, and advanced bioinformatics tools, continuous validation remains necessary before commercial release.

Another challenge is the efficient delivery of CRISPR components into plant cells. While *Agrobacterium tumefaciens*-mediated transformation and particle bombardment are commonly used, many economically important crops and elite breeding lines remain difficult to transform and regenerate. Developing genotype-independent transformation methods is therefore an active area of research. Many important agronomic traits, including grain yield, drought tolerance, nutrient-use efficiency, and climate resilience, are controlled by multiple interacting genes. Editing a single gene often produces only modest improvements. Consequently, future breeding programs will increasingly rely on multiplex genome editing, where several genes are modified simultaneously to achieve greater genetic gains.

4.2 Biosafety and Environmental Considerations

Genome edited crops have generated considerable discussion regarding biosafety and ecological sustainability. Unlike traditional transgenic crops, many CRISPR-edited plants do not contain foreign DNA after the editing process, particularly when DNA-free editing systems are employed. This characteristic has prompted scientists to argue that certain genome-edited crops resemble naturally occurring mutations or conventionally bred varieties.

Nevertheless, comprehensive biosafety evaluations remain essential before field release. Researchers must assess potential unintended effects on plant metabolism, interactions with beneficial organisms, biodiversity, and long-term ecosystem stability. Transparent scientific evaluation and continuous post-release monitoring will help ensure responsible deployment of genome-edited crops. Importantly, CRISPR technology also supports environmental sustainability by reducing dependence on synthetic pesticides, fungicides, and chemical fertilizers. Disease-resistant and stress-tolerant crop varieties can lower agricultural inputs, improve resource-use efficiency, and reduce greenhouse gas emissions associated with intensive farming practices.

4.3 Regulatory Framework Across the World

The regulation of genome-edited crops varies considerably among countries. Several nations evaluate genome-edited plants according to the characteristics of the final product rather than the breeding method used to develop them. In contrast, some countries regulate genome-edited crops under frameworks similar to those applied to genetically modified organisms (GMOs).

Countries such as the United States, Japan, Argentina, Brazil, and Australia have adopted relatively flexible regulatory approaches for certain genome-edited crops that do not contain foreign DNA. These policies have encouraged innovation and accelerated commercialization. Conversely, regulatory processes in some regions remain more stringent, resulting in longer approval timelines. India has also taken important steps toward developing an enabling regulatory environment for genome editing. Recent policy updates have distinguished selected genome-editing approaches from conventional transgenic technologies, creating new opportunities for agricultural research while maintaining biosafety oversight.

International harmonization of regulatory policies will be crucial for facilitating global trade, encouraging innovation, and ensuring public confidence in genome-edited agricultural products.

Table 3. Regulatory Status of Genome-Edited Crops in Selected Countries

Country	Regulatory Approach	Current Status
India	Gene-editing guidelines introduced	Regulatory pathway evolving
United States	Product-based	Several genome-edited crops approved
Japan	Product-based	Commercial cultivation permitted for selected crops
Argentina	Case-by-case assessment	Supportive regulatory framework
Brazil	Product based	Rapid approval pathway available
Australia	Relaxed regulation for SDN-1 edits	Research and commercialization progressing
European Union	Process-based (under revision)	Policy discussions ongoing

4.4 Ethical and Societal Considerations

The long-term success of CRISPR technology depends not only on scientific advancements but also on public trust. Transparent communication regarding the benefits, risks, and limitations of genome editing is essential to address misconceptions and improve consumer acceptance. Ethical considerations include equitable access to genome-editing technologies, intellectual property rights, affordability for smallholder farmers, and protection of indigenous crop genetic resources. Public-private partnerships, responsible innovation, and science-based policymaking will play important roles in ensuring that the benefits of CRISPR are shared broadly across society.

4.5 Future Perspectives

The future of CRISPR-based crop improvement is exceptionally promising. Recent developments in base editing, prime editing, epigenome editing, and DNA-free genome editing are enabling increasingly precise genetic modifications while minimizing unintended changes. The integration of CRISPR with artificial intelligence (AI), genomic selection, speed breeding, high-throughput phenotyping, remote sensing, and digital agriculture is expected to transform plant breeding into a faster, more predictive, and data-driven discipline. AI-assisted identification of candidate genes, combined with rapid genome editing and accelerated breeding cycles, will significantly shorten the time required to develop superior crop varieties.

Future research is also expected to focus on de novo domestication of wild crop relatives, improvement of orphan crops, enhancement of photosynthetic efficiency, biological nitrogen fixation, carbon sequestration, and breeding for climate resilience. These innovations will contribute directly to achieving the United Nations Sustainable Development Goals by improving food security, reducing environmental impacts, and strengthening agricultural resilience.

Overall, CRISPR technology is evolving from a powerful research tool into an essential component of modern crop improvement programs. With continued scientific innovation, effective regulatory frameworks, and responsible implementation, genome editing has the potential to reshape global agriculture and support sustainable food production for future generations.

Major Indian institutes working on CRISPR crop improvement

- Indian Council of Agricultural Research (ICAR)
- Indian Agricultural Research Institute (IARI)
- Indian Institute of Rice Research (IIRR)
- Indian Institute of Wheat and Barley Research (IIWBR)
- Indian Institute of Pulses Research (IIPR)
- National Research Centre for Banana (NRCB)
- Indian Institute of Vegetable Research (IIVR)

Conclusion

CRISPR-based genome editing has emerged as one of the most transformative innovations in modern plant breeding, offering precise, efficient, and rapid improvement of economically important crop traits. Its successful application in enhancing yield, nutritional quality, disease resistance, and tolerance to abiotic stresses demonstrates its immense potential to support sustainable agriculture and global food security. Advanced technologies such as base editing, prime editing, and multiplex genome editing have further increased the accuracy and versatility of crop improvement. However, challenges related to efficient gene delivery, off target effects, regulatory policies, biosafety, and public acceptance must be addressed to enable wider adoption. Future progress will depend on integrating CRISPR with genomics, artificial intelligence, speed breeding, and precision agriculture to accelerate the development of climate-resilient and resource-efficient crop varieties. With continued scientific innovation, responsible regulation, and collaborative research, CRISPR has the potential to reshape global agriculture and contribute significantly to sustainable food production for future generations.

References

1. Ahmad, S., Tang, L., Shahzad, R., et al. (2021). CRISPR-Based Crop Improvements: A Way Forward to Achieve Zero Hunger. *Journal of Agricultural and Food Chemistry*, *69*(30), 8307–8323.
2. Arora, L., & Narula, A. (2017). Gene editing and crop improvement using CRISPR-Cas9 system. *Frontiers in Plant Science*, *8*, 1932.
3. Bortesi, L., & Fischer, R. (2015). The CRISPR/Cas9 system for plant genome editing and beyond. *Biotechnology Advances*, *33*, 41–52.
4. 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.
5. Gao, C. (2021). Genome engineering for crop improvement and future agriculture. *Cell*, *184*(6), 1621–1635.
6. Gao, Y., & Zhao, Y. (2023). CRISPR/Cas Technology Revolutionizes Crop Breeding. *Plants*, *12*(17), 3119.
7. Jaganathan, D., Ramasamy, K., Sellamuthu, G., Jayabalan, S., & Venkataraman, G. (2018). CRISPR for crop improvement: An update review. *Frontiers in Plant Science*, *9*, 985.
8. Kaur, N., Qadir, M. Q., Francis, D. V., et al. (2025). CRISPR/Cas9: A sustainable technology to enhance climate resilience in major staple crops. *Frontiers in Genome Editing*, *7*.
9. Li, C., Zong, Y., Wang, Y., et al. (2018). Expanded base editing in rice and wheat using a Cas9-adenosine deaminase fusion. *Genome Biology*, *19*, 59.
10. Li, J., Manghwar, H., Sun, L., et al. (2019). Whole genome sequencing and CRISPR/Cas genome editing for crop improvement. *Journal of Genetics and Genomics*, *46*, 555–567.
11. Mahas, A., Mahfouz, M. (2024). Crop bioengineering via gene editing: Reshaping the future of agriculture. *Plant Cell Reports*, *43*, Article 98.
12. Singh, V., Braddick, D., & Dhar, P. K. (2017). Exploring the potential of genome editing CRISPR-Cas9 technology. *Gene*, *599*, 1–18.
13. Tuncel, A., Pan, C., Clem, J. S., et al. (2025). CRISPR–Cas applications in agriculture and plant research. *Nature Reviews Molecular Cell Biology*, *26*, 419–441.

14. Wang, M., Lu, Y., Botella, J. R., Mao, Y., Hua, K., & Zhu, J.-K. (2017). Gene targeting by homology-directed repair in rice using CRISPR-Cas system. *Molecular Plant*, *10*, 1007–1010.

15. Xu, R., Li, J., Liu, X., et al. (2020). Development of plant genome editing technologies. *Nature Plants*, *6*, 729–742.

16. Zaidi, S. S.-e.-A., Mahfouz, M. M., & Mansoor, S. (2017). CRISPR-Cpf1: A new tool for plant genome editing. *Trends in Plant Science*, *22*(7), 550–553.

17. Zhang, Y., Massel, K., Godwin, I. D., & Gao, C. (2018). Applications and potential of genome editing in crop improvement. *Genome Biology*, *19*, 210.

18. Zhu, H., Li, C., & Gao, C. (2020). Applications of CRISPR-Cas in agriculture and plant biotechnology. *Nature Reviews Molecular Cell Biology*, *21*, 661–677.