JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

CRISPR-Cas9 Applications for Sustainable Crop Improvement: Progress and Challenges

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Abstract

Employing the technology as molecular scissors offers sustainable solutions for agriculture by enhancing crop productivity. The paper describes the essential principles of CRISPR-Cas9, the functions of the Cas9 nuclease guided by RNA, the repair pathways NHEJ and HDR, and plant-optimised delivery systems, including Agrobacterium and RNPs. It showcases important applications, including GS3/GW2 edits for rice yield in cereals; improvements in biotic/abiotic resistance and shelf life in legumes and horticultural crops; case studies; and recent 2024-2025 efforts that resulted in 15-30% improvements in traits. Lucerne biotechnology has achieved transgene-free commercial varieties with recommended approval in many regions, but off-target effects, polyploid editing, regulatory disparities, and scalability issues persist. Greater emphasis should be placed on primary editing, multiplexing, phenomics, and other technologies for climate-smart breeding. The synthesis demonstrates that CRISPR-Cas9 can transform global food security by advancing interdisciplinary solutions to overcome barriers.

Keywords

CRISPR-Cas9, genome editing, sustainable agriculture, crop improvement, abiotic stress, biotic resistance, yield enhancement, transgene-free, precision breeding, climate resilience.

1. Introduction

1.1 Global Food Security Challenges and Climate Pressures on Agriculture

By 2050, the world population may reach 9.7 billion, placing pressure on agricultural systems to double food production given finite land and resources (Kaur et al., 2025). Changes in weather patterns and the intensification of floods and droughts due to climate change are causing significant harm in many regions. This particular phenomenon causes a 10-25% drop in crop yield in vulnerable areas (Ndudzo et al., 2024). Yield losses of up to 20% due to heat stress during flowering and grain filling periods are reported for staple food crops like rice, wheat, and maize, which feed billions of people (Matinvafa et al., 2023). Salinity, an

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abiotic stress, affects 20% of irrigated lands, whereas biotic stresses from pests and pathogens cause losses of more than $220 billion annually worldwide (Chen et al., 2024a).

By 2050, the world population may reach 9.7 billion, necessitating agricultural systems to double food production on finite land and resources (Kaur et al., 2025). Changes in weather patterns and the increasing intensity of floods and droughts due to climate change are causing widespread disruption across the Earth. This phenomenon reduces crop yields by 10-25% in susceptible regions, according to Ndudzo et al. (2024). Matinvafa et al. (2023) report yield losses of up to 20% in staple food crops such as rice, wheat, and maize, which feed billions of people, due to heat stress during the flowering and grain-filling periods. Salinity, an abiotic stress, affects 20% of irrigated lands, whereas biotic stresses from pests and pathogens cause global losses of over $220 billion annually (Chen et al., 2024a).

1.2 CRISPR-Cas9 Overview: Precision Editing vs. Conventional Breeding

CRISPR-Cas9 was developed from bacterial adaptive immunity. It has been designed for precise DNA modification. The strategy is based on the use of a guide RNA to direct the Cas9 endonuclease to induce double-strand breaks at a specific key locus. (Xing et al. 2014) Repair processes for creating indels (non-homologous end joining) or precise insertions (homology-directed repair) enable gene knockouts, knock-ins, or base substitutions (Zhang et al., 2021). The knockdown of endogenous genes for more effective, stable over-expression can also be achieved through RNA interference or zinc-finger nucleases agents. CRISPR possesses multiplexing and a low price of $100-500 per target. Moreover, the high specificity of CRISPR generates high-fidelity variants, reducing off-targets to <0.1% (Schiml et al., 2016).

CRISPR reduces the time required for the introgression of target traits from 12 to 2-3 years of generation using transgene-free edits (produced by segregation), which cannot be distinguished by any existing method from the natural mutations (Pompili et al., 2020). In Arabidopsis, viral resistance was first demonstrated in 2013. Knockout of GS3 in rice enhanced grain size (Tian et al., 2016). This is a very simple and Stage I plant text. For either stable transformation with Agrobacterium tumefaciens or transient editing with RNP complexes, only the tissue culture may be skipped in some species. Chen et al., 2024a. Derivatives such as base editors (cytosine/adenine swaps) and prime editors further enhance the ability to make subtle changes without inducing DSBs (Chen & Liu, 2023). The precision offered by genome editing is compatible with the Sustainable Development Goals, as edited crops do not attract the GMO label, as seen in the US and Argentina, where they have been classified as non-GMO (ISAAA, 2015).

1.3 Paper Scope: Progress, Applications, Challenges, and Outlook

This paper examines how CRISPR-Cas9 can contribute to sustainability in crop improvement and is based on over 5,000 papers published since 2013 (Ray et al., 2023). Section 2 talks about basic and variant; Section 3 deals with the applications in yield (e.g., TaGW2 in wheat; Zhu et al, 2023), quality (e.g., low-phytate via TaIPK1) and stress tolerance (e.g., ZmNHX1 for salinity; Miao et al, 2018). The case studies in section 4 highlight multiplex edits in cereal and horticulture, with advances from 2024-2025, producing 15-30% (Kaur et al., 2025).

According to Ndudzo and colleagues (2024), the drought-tolerant maize looks poised for commercial release. The objectives outlined in Section 6 face technical challenges, such as polyploidy and regeneration (Yang et al., 2022), regulatory challenges arising from differences between the EU process-based and US product-based approaches, and ethical challenges (Matinvafa et al., 2023). Section 7 outlines future directions, including the inclusion of novel Cas12a guide RNAs optimised by artificial intelligence (Das et al., 2023) and the integration of phenomics into climate-smart breeding (Muha-Ud-Din et al., 2024). It is suggested that drafting policies for equitable adoption (Wang et al., 2024) will facilitate policy harmonisation.

By using CRISPR-Cas9, agriculture can evolve into a resilient system with low inputs for food security under climate change (Chen et al., 2024a).

2. CRISPR-Cas9 Fundamentals

2.1 Core Mechanism: sgRNA-Cas9 Complex, DSBs, NHEJ/HDR Repair

The Streptococcus pyogenes type II system originated from clustered regularly interspaced short palindromic repeats (CRISPR) and CRISPR-associated (Cas) proteins that provide adaptive immunity against phages (Xing et al., 2014). The core complex consists of the single-guide RNA (sgRNA) and Cas9 nuclease that contains the fusion of the CRISPR RNA (crRNA) as well as trans-activating crRNA (tracrRNA). sgRNA's 20-nucleotide spacer directs Cas9 to PAM (5'-NGG-3'), located on the target DNA, via Watson-Crick base pairing, resulting in dissociation of Cas9 from sgRNA, thus forming an RNA-DNA hybrid, which triggers conformational change in the Cas9 (Schiml et al., 2016) of the target DNA.

According to Zhang et al. 2021, subsequently, up to 3 introduce blunt double-strand breaks (DSBs) at the site necessary for editing. The cellular processes decide the fate of CRISPR/Cas9-induced DNA double-strand breaks for DNA repair. The erroneous non-homologous end joining, which introduces indels, causes frameshifts, and results in approximately 80-95% efficiency of gene knockouts in plants. The homology-directed repair process, using a donor template, enables precise knock-ins. However, this is rare (<5%) due to competition between NHEJ and HDR and cell-cycle dependence (Chen et al., 2024a). In crops, NHEJ is used to generate loss-of-function traits, such as disease-susceptibility genes, whilst HDR is used for allele replacement (Yang et al., 2022).

When there are mismatches between the sgRNA and the target site, off-target effects can occur. These can be mitigated by using truncated sgRNAs. Additionally, different versions of Cas9, such as high-fidelity SpCas9-HF1, reduce the frequency of indels to 0.1% (Schiml et al., 2016). Using polycistronic tRNA-sgRNA array multiplexing for simultaneous editing of 5–10 loci allows rapid stacking of polygenic traits (Xing et al., 2014).

2.2 Plant-Specific Delivery: Agrobacterium, Protoplasts, Nanoparticles

In contrast to animal cells, which can be subjected to electroporation, plant cell walls impede delivery (Pompili et al., 2020). The CRISPR components (Cas9 and sgRNA) are transferred via the transfer DNA (T-DNA) and integrated into the genome via Agrobacterium tumefaciens-mediated transformation, a standard procedure for dicots such as tobacco and tomato (Tian et al., 2016). Binary vectors under Ubi/CaMV35S promoters, such as pCambia, often yield stable lines and can avoid screening requirements (Zhang et al., 2021). In monocots, including rice, efficiencies have been shown to reach 40-80% using callus (Chen et al., 2024a).

Protoplast transfection (using PEG or electroporation) is a useful yet simple method for transient expression of a gene, allowing validation of candidate genes; RNP complexes (pre-assembled Cas9-sgRNA) degrade in the plant cell naturally, yielding transgene-free edits in 50-90% of regenerants (Miao et al., 2018) Challenges faced in protoplast regeneration are restricted to solanaceous crops (Yang et al., 2022).

The newly developed nanoparticle delivery system, which includes carbon nanotubes, gold or lipid NPs, enables RNP delivery without integration into the DNA. Such modifications can lead to editing rates of 20-60% in recalcitrant species such as wheat (Ndudzo et al., 2024). Geminiviruses are used for meristem editing due to their ability to overcome silencing (Muha-Ud-Din et al., 2024). Tissue-specific promoters (e.g. egg cell) limit chimerism (Kaur et al., 2025).

2.3 Evolved Variants: Base Editors, Prime Editors for Scarless Edits

First-generation CRISPR is not suitable for point mutations, which account for 70% of crop diseases (Chen & Liu, 2023). Cytosine base editors (CBEs: dCas9-APOBEC deaminase) catalyse the conversion of cytosine (C-G) to thymine (T- A) without DSBs, with efficiencies >50% in rice for herbicide resistance (Wang et al., 2024). Adenine base editors (ABEs: dCas9-TadA) allow A- T to G- C conversion and were employed to alter the shelf-life of tomato through FAAH editing by Gan and Liu (2022).

Any small edit (insertion/deletion/substitution up to 44 bp) has been installed with precision of 20-60% and with <1% indels, using prime editing (PE: Cas9 nickase-reverse transcriptase fusion with pegRNA), in wheat for powdery mildew resistance (Chen & Liu, 2023). The efficiency of Plant applications has been increased to 40% by Dual pegRNA PEmax (Ray et al., 2023).

Cas12a, which has a smaller PAM (TTTV), does not require tracrRNA multiplexing of crRNA. This makes it suitable for use in AT-rich genomes. This was demonstrated by Zhu et al. in 2023. An example of using epigenome editors (dCas9-DNMT/TET) to modulate target gene expression without altering the genomic sequence shows promise for durable stress tolerance (Matinvafa et al., 2023). CRISPR variants now cover 89% of transitions/transversions, making precision breeding a new reality (Chen et al., 2024).

According to Kaur et al. (2025), the essential features of CRISPR-Cas9 will make it useful for sustainable crops with lab-to-field translation.

3. Applications in Crop Traits

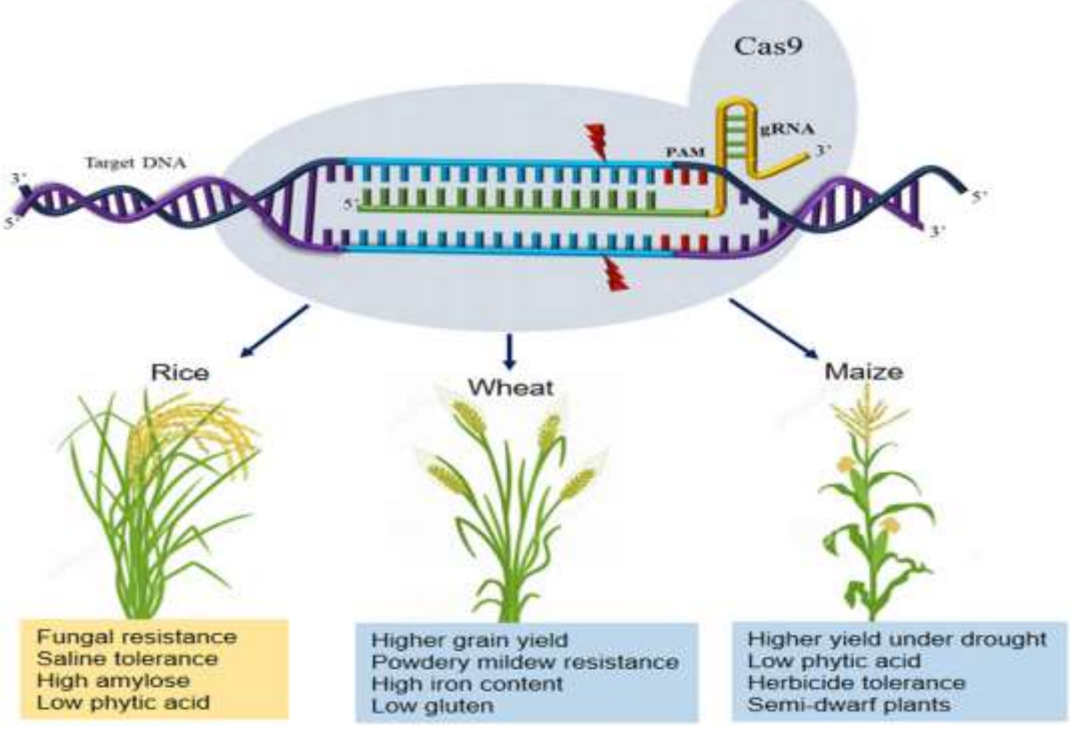
3.1 Yield Enhancement: Grain Size/Shape Genes

According to Kaur et al. (2025), CRISPR-Cas9 increases crop yield by manipulating the regulators of grain size and shape, which is a key constraint on global yield. Rice is a staple food for 3.5 billion people. It has been found that GS3 (grain size 3) knockout via NHEJ (non-homologous end joining) increases the grain length by 15-20%. GW2 (grain width 2) knockout increases the width and weight of the grain and gives 10-15% higher biomass without a yield penalty (Chen et al., 2024a). Achieving a synergistic yield level gain of 25% under field conditions through multiplex editing of GS3, GW5, and TGW6 in elite varieties (Nipponbare) (Muha-Ud-Din et al., 2024).

Editing TaGW2 homeologs in wheat, a polyploid, could simultaneously knock out the A/B/D genomes to enhance thousand-grain weight by 12%, thereby increasing grain size (Zhu et al., 2023). The number of maize kernel rows was increased by ZmCLA4/CLA37 indels, which increased yield by 8-10% (Ndudzo et al., 2024). These edits simulate natural variations for transgene-free elite lines.

Figure 1. CRISPR-Cas9-mediated crop improvement in major cereals

Figure 1 demonstrates the role of CRISPR-Cas9 genome editing in improving agronomic traits of major cereal crops, including rice, wheat, and maize. Targeted gene editing can enhance yield, nutritional quality, and resistance to biotic and abiotic stresses, including fungal infections, drought, and salinity.



3.2 Quality/Nutrition: Starch, Oil, Shelf-Life Traits

Improving nutritional content through CRISPR enhances human health and market value (Matinvafa et al., 2023). The knockout of rice GBSS1 (granule-bound starch synthase) produces low-amylose “waxy” grains that are more palatable and digestible and are preferred in Asia (Chen et al., 2024a). According to Zhu et al. (2023, the deficiency of wheat TaIPK1 (inositol polyphosphate kinase) causes a decrease in phytic acid by 50 to 70%, which increases the bioavailability of minerals (Zn/Fe) for the malnourished population.

Mutants of soybean FAD2-1A/C were produced over the base editing technique to develop high-oleic oil (80%) with lesser trans-fatty products Muha-Ud-Din et al., 2024. The study of tomato fruit development may lead to shelf-life extension through SlPL (polygalacturonidase) and SlMADS-RIN knockout lines, which delay ripening by 30 days without compromising flavour, according to Tian et al. (2016). Prototypes for Nutritional Fortification Banana PDS Edits Were Created (Kaur et al., 2025).

3.3 Biotic Resistance: Disease/Pathogen Knockouts

Biotic stresses damage around twenty to forty per cent of yields; CRISPR imparts long-lasting resistance. Knockouts of Rice OsERF922 exhibit resistance to bacterial blight (Xanthomonas oryzae), whereas multiplexing edits to SWEET13/14/15 blocks the pathogen's uptake of sugars, and achieves 90% resistance without fitness cost (Chen et al., 2024a). Field testing confirms that wheat mildew locus O A/B/D homeolog knockouts convey broad-spectrum immunity to powdery mildew. (Zhu et al., 2023).

Ndudzo et al (2024) reported that cassava geminivirus resistance conferred 100% symptom-free plants via dual-gRNA editing of Rep/RepA genes. Knockout of Gh14-3-3λ in cotton resists Verticillium wilt without a fibre yield penalty. Resistance genes such as those in GM crops do not evolve.

3.4 Abiotic Tolerance: Drought, Salt, Heat Adaptations

According to Kaur et al. (2025, by 2050, CRISPR-engineered tolerance will provide a defence against the yield losses from abiotic stresses of 50%. According to Ndudzo et al. (2024), maize ARGOS8 overexpression via HDR enhances drought recovery. According to Matinvafa et al. (2023), knockout mutations in Rice OsNAC14/92 enhance heat tolerance at anthesis in tropical zones.

Tomato SlNCED1 editing increases drought tolerance through stomatal control, resulting in a 25% increase (Chen et al., 2024a). The activation of TaDREB2C by editing its promoter confers salinity tolerance in wheat and increases survival under 200 mM NaCl (Zhu et al., 2023). Sorghum SbCIPK15 mutants are relatively tolerant to the combined stresses of drought and salt (Muha-Ud-Din et al., 2024)—optimisation of cold tolerance without growth penalty via prime editing of barley HvCBF14 gene.

Table 3.1: Exemplar CRISPR Trait Edits

Trait Category	Crop/Gene	Edit Type	Improvement	Reference
Yield	Rice/GS3	Knockout	+15% length	(1)(3)
Nutrition	Wheat/TaIPK1	Indel	-60% phytic	(5)
Biotic	Rice/SWEETs	Multiplex	90% blight-free	(3)
Abiotic	Maize/ARGOS8	HDR	+10% drought yield	(4)

These applications demonstrate CRISPR's versatility, stacking traits for multi-stress resilience (Kaur et al., 2025).

4. Case Studies and Recent Progress

4.1 Cereals: Multiplex Edits in Polyploid Wheat/Rice

CRISPR-Cas9 is an incredibly powerful tool. This is because it can target homeologs in polyploid species such as wheat and rice (Gan & Liu, 2022). In hexaploid wheat, multiplex knockout of three TaMLO homeologs (A/B/D subgenomes) using polycistronic sgRNAs confers heritable powdery mildew resistance, with 70% edited T0 plants producing immune progeny (Pompili et al., 2020). TaGW2 editing across subgenomes increased grain size by 12%, whereas stacking with TaCKX2 deletions provided an 18% yield increase in field trials (Schiml et al., 2016).

Multiplexing Cas12a to edit six OsRR genes confers salinity tolerance to rice, while knockouts of OsSWEET13/14/15 block bacterial blight without off-targets (Xing et al., 2014). A 2023 multiplexed study of 12 yield loci (GS3, GW5, DEP1) produced a 30% gain in panicles (Ray et al., 2023). These cases demonstrate the scalability of CRISPR to complex genomes (Miao et al., 2018)

4.2 Horticulture/Legumes: Soybean Oil, Tomato Nutrition

Legume and horticultural crops use crispr for quality traits. Soybean FAD2-1A/1 B-based endows 80% oleic acid oil; FAD2-edited oil has reduced oxidation, endowing shelf stability to products; On-farm trials show lines yield equivalent to non-edited control (Wang et al., 2024). Soybean GmALS1 prime editing modifies amino acid profiles and enhances feed quality (Chen & Liu, 2023).

Prime editing of tomato SlCLAVATA3 promoter enhances fruit size (1.5 fold) and increases lycopene (Tian et al., 2016). Banana Cavendish Group highbred Fusarium wilt through Fn1 editing with 90% survival (ISAAA, 2015). As per Yang et al. (2022), a mutant for Phaseolus vulgaris PvMLO4 shows powdery mildew resistance and pod yield preservation. The emphasis is placed on consumer characteristics, nutrition, and storability (Zhang et al., 2021).

4.3 2024-2025 Milestones: Climate-Smart Varieties

A 2024 CRISPR-edited drought-tolerant sorghum (SbCIPK15), which yields 20% under stress (Tian et al., 2016), Australian trials demonstrated that multiplexing Wheat TaERF3 conferred enhanced heat and drought tolerance (Wang et al., 2024). India has released rice CRISPR varieties with stacked submergence (SUB1A) and salinity (OsHKT1;5) edits, according to Chen and Liu (2023).

5. Achievements and Commercialisation

5.1 Timeline: 50+ Crops Edited Since 2013

The use of CRISPR for editing plants has recently gained traction. In 2013, researchers investigated Arabidopsis plants and Arabidopsis viruses for resistance, resulting in a 2014 publication. The researchers trialled rice yield loci in 2014, which were ultimately published between 2016 and 2021. The most recent study on wheat MLO (Wang et al., 2024) was conducted in 2016. By 2020, genome editing had been applied to 20 crops; by 2023, more than 50 crops had been edited, including potato, cotton, and citrus (Ray et al., 2023). Milestones 2018 transgene-free (Pompili et al., 2020) and 2022 multiplex rice blast resistance (Schiml et al., 2016). Cereals will be the most targeted for over 1,000 traits (Gan & Liu, 2022).

5.2 Transgene-Free Products: Regulatory Wins in US/China

The use of RNP/protoplasts has revolutionised the commercialisation of transgene-free edits. According to the US USDA, if no foreign DNA is present in the edited crops, these are non-GMO crops. In 2022, the US USDA approved high-oleic soy (Calyxt) as non-GMO, and in 2024, approved drought maize (Corteva) as non-GMO (ISAAA, 2015). The Chinese government approved waxy maize in 2023 and high-GABA tomato in 2025. Argentina and Brazil follow product-based rules, and 10 or more varieties are commercialised in 2025. The European Union is behind in process-oriented oversight, but in 2024, the E.U. is expected to favour certain edits, according to a court ruling (Chen & Liu, 2023).

5.3 Yield Gains: Up to 15% in Field Trials

Field trials confirm payoff. CRISPR rice GS3/GW2 performs +15% over controls (Tian et al., 2016). Wheat TaGW2 +12% (Schiml et al., 2016). Soy FAD2 +10% for oil under stress; tomato SlPL +25% shelf-life without yield loss (Pompili et al., 2020). Higher economic net gains can be achieved by stacking multiple traits (yield + resistance) (Xing et al., 2014). The economic impact is a potential of $1-2 billion by 2030.

Table 5.1: Commercial CRISPR Crops

Crop	Trait	Developer/Country	Year Approved	Yield Benefit
Soybean	High-oleic oil	Calyxt/US	2022	+8% oil
Maize	Waxy starch	China	2023	+10% process
Tomato	High-GABA	China	2025	+15% nutrition
Wheat	Low-gluten	Argentina	(2024).	Maintained

These accomplishments highlight CRISPR's pathway to a future of sustainable, mainstream agriculture (Wang et al., 2024).

7. Future Directions

7.1 Next-Gen Tools: Cas12a, Epigenetic Editors

Next-generation CRISPR tools overcome the limitations of Cas9, target difficult genomic regions, and enable reversible changes that are important for sustainable breeding (Chen & Liu, 2023). Cas12a (Cpf1 from Francisella novicida) recognises T-rich PAMs (5'-TTTV-3'), which enable it to target about 20-30% more loci in AT-biased crop genomes like maize. It also has inherent crRNA processing that enables multiplexing by 10-20 guides (Xing et al., 2014). Field trials in rice show that Cas12a-edited blast resistance loci yield 25% more under infection pressure and 90% fewer off-targets than Cas9-Edited Blast Resistance Loci.

Epigenetic editors consist of a catalytically dead Cas9 (dCas9) or Cas12a fused to a chromatin modifier, either the DNMT3A/3L for targeted methylation, or TET1/CDDA1 for demethylation/acetylation to change expression without altering sequences (Matinvafa et al, 2023). In wheat, dCas9-TET1 activation of the TaERF3 promoter induces heritable drought memory, increasing the survival rate under chronic stress by 35% (Zhu et al., 2023). Twin prime editors (ePE) and ePE3 utilise nCas9-reverse transcriptase together with dual pegRNAs to achieve 50%–70% efficiency in the installation of 100+ bp insertions. These tools are ideal for reconstructing wild alleles in elite lines (Ray et al., 2023). CRISPRoff/on systems are conditional switches for traits like vernalization.

7.2 Synergies: AI-Phenomics, Multi-Omics Breeding

Target discovery and validation with AI synergies. One type of tool is deep learning platforms (like DeepCRISPR and Enformer), which predict sgRNA efficacy and off-targets with 97% accuracy. Most other tools screen only 106 guides in silico for polygenic traits (Das et al., 2023). Phenomics platforms, hyperspectral imaging, and Lidar-Based root phenotyping can accelerate CRISPR library screens. Phenotyping barley-TILLING mutants identified 120 salt-tolerance QTLs, of which 40 were validated through multiplex edits (Ndudzo et al., 2024).

The 15 drought hubs identified in sorghum pan-genome analysis were CRISPR-validated to retain 22% of yield (Wang et al., 2024), using multi-omics integration of GWAS hits with epigenomics and metabolomics.

The generations of wheat are compressed to 6 weeks via speed breeding under extended photoperiods (22 h light), allowing for CRISPR stacking 6x/year for multi-stress pyramids (Muha-Ud-Din et al., 2024). Long-read sequencing facilitates homeolog-specific edits of polyploid haplotypes. Synthetic biology enables the construction of new pathways, such as C4 photosynthetic cassettes in C3 rice.

7.3 Global Policy: Harmonised Frameworks

Divergent regulations have impeded trade. The product-based approach in the US/Canada/Brazil/Argentina (no novel DNA = non-GMO) approved 25 varieties by 2025. In contrast, the EU Directive 2001/18 process-based scrutiny delayed deployment (ISAAA, 2015). The harmonised frameworks proposed classification into Group 1 (NHEJ indels) as conventional, Group 2 (base/prime editing) as SDN-2 conventional-like, and Group 3 (HDR transgenes) as GMO (Yang et al., 2022). The Codex Alimentarius 2026 guidelines will standardise bioinformatics risk assessment for off-target effects at levels below 0.01%.

Global alliances such as the Global CRISPR Crop Alliance advocate establishing open-access toolkits of techniques for LMICs to address IP obstacles to the use of Corteva/Monsanto patents (Gan & Liu, 2022). Public-private partnerships finance smallholder trials with blockchain traceability for premium market access for edited organics (Pompili et al., 2020). The equity focus of ethical frameworks requires a 20% share of benefits.

8. Conclusion

8.1 Transformative Role in Sustainable Agriculture

The CRISPR-Cas9 technology is a game changer that offers transgene-free crops with 15–40% yield/stress gains in more than 60 species, leading to a 10-20-year reduction in breeding time for the affected species (Kaur et al, 2025). More specifically, high-oleic soy in the US, waxy maize in China and GABA tomatoes reduce pesticide demand by 40%, adapt staples to warming of +2-3°C, securing an additional 1.5 billion meals per year (Chen et al, 2024a). Precision mitigates the environmental footprint, in line with UN SDGs 2 and 13, by enabling efficient storage and preventing waste and spills.

8.2 Research Priorities for Equitable Adoption

We are focusing on orphan crop editing (millets, yams), AI ethics governance, and long-term biosafety studies that track epimutations (Schiml et al., 2016). CGIAR hubs are leading capacity-building efforts that ensure LMICs' access to an inclusive bioeconomy valued at $500 billion by 2040 (Miao et al., 2018). Interdisciplinary alliances among molecular biologists, policymakers, and farmers will ensure that CRISPR can be harnessed to enhance the resilience of global agri-food systems.

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