Life Science Review
Journal homepage: https://lsr.crcjournals.org/ 2023

The Role of CRISPR and Genome Editing Technologies in Shaping the Future of Agriculture and Healthcare

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Abstract

CRISPR and related genome editing technologies have rapidly transitioned from laboratory tools to foundational platforms reshaping agriculture and healthcare. By enabling precise, efficient, and scalable modification of genetic sequences, CRISPR-Cas systems accelerate basic discovery, therapeutic development, and crop improvement. In healthcare, in vivo and ex vivo editing strategies target monogenic disorders, cancer, infectious diseases, and polygenic risk through somatic interventions, while advances in delivery, specificity, and off-target control expand clinical feasibility. In agriculture, genome editing enhances yield, resilience to biotic and abiotic stresses, nutritional quality, and sustainability by producing traits that are difficult or slow to obtain with conventional breeding. Emerging modalities—base and prime editing, epigenome editing, and RNA-targeting systems—further refine precision and functional scope. Yet the acceleration of editing technologies raises critical ethical, ecological, and governance questions, including equitable access, germline boundaries, biosafety, gene drive oversight, intellectual property, and public trust. This paper surveys the current landscape of CRISPR applications across agriculture and healthcare, highlights technical advances and translational milestones, and outlines the regulatory, ethical, and social frameworks necessary to steer genome editing toward equitable, safe, and sustainable futures.

Keywords: CRISPR, Genome editing, Agriculture, Healthcare, Base/Prime editing

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Introduction

The advent of CRISPR-Cas systems transformed genome manipulation from a specialized, low-throughput capability into a broadly accessible, programmable technology. Derived from bacterial adaptive immunity, CRISPR nucleases (e.g., SpCas9, Cas12a) use guide RNAs to direct sequence-specific DNA cleavage, after which cellular repair pathways effect targeted modifications. Subsequent innovations—high-fidelity nucleases, nickases, base editors, prime editors, and epigenome editors—have improved precision, minimized double-strand breaks, and expanded editable target space. Parallel progress in delivery vehicles (lipid nanoparticles, AAV/adenoviral vectors, ex vivo engineered cells) enables clinical and agronomic translation.

In healthcare, CRISPR has moved swiftly from proof-of-concept to clinical testing and early approvals in somatic contexts, including ex vivo edited hematopoietic stem cells for hemoglobinopathies and engineered T cells for oncology. In agriculture, genome-edited crops with disease resistance, drought tolerance, and improved nutrition illustrate paths to climate resilience and reduced chemical inputs. As editing scales, questions of safety (off-targets, on-target complexities), ecological impact (gene flow, gene drives), ethics (germline editing), and justice (access, benefit sharing, intellectual property) become central.

This paper synthesizes the state of CRISPR and genome editing across two pillars—agriculture and healthcare—through five focused themes: technical foundations and precision advances; therapeutic editing; crop improvement and sustainable agriculture; delivery, safety, and measurement; and ethics, regulation, and equitable implementation.

Subheadings

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1. Technical Foundations and Precision Advances

Second-generation editors reduce reliance on double-strand breaks: cytosine and adenine base editors enable targeted C→T/G→A conversions; prime editing writes small insertions, deletions, and all transition/transversion changes with pegRNAs; Cas variants (Cas12a, SaCas9, SpRY) expand PAM compatibility; and CRISPRi/a and epigenome editors modulate gene expression without altering sequence. Computational guide design and off-target prediction, together with high-fidelity nucleases, improve specificity.

2. Therapeutic Genome Editing in Healthcare

Ex vivo editing of hematopoietic stem cells and T cells enables treatment of β-hemoglobinopathies, immuno-oncology (e.g., PD-1/CIK/TCR edits), and primary immunodeficiencies. In vivo editing targets liver, eye, and muscle via LNPs and viral vectors for transthyretin amyloidosis, inherited retinal diseases, and dystrophies. Antiviral strategies (latent viral DNA disruption) and polygenic risk modulation are emerging. Key hurdles include durable efficacy, mosaicism, immune responses to editors, and scalable GMP manufacturing.

3. Crop Improvement and Sustainable Agriculture

CRISPR accelerates trait stacking for yield, disease resistance (e.g., mildew, blight), pest resilience, enhanced photosynthesis, and abiotic stress tolerance (drought, salinity, heat). Nutritional traits (biofortified oils, vitamins, reduced allergens/antinutrients) and quality traits (texture, shelf life) advance food security and reduce waste. Multiplex editing and de novo domestication of orphan crops broaden biodiversity and regional resilience, while gene-edited microbial consortia support soil health and nitrogen use efficiency.

4. Delivery, Safety, and Measurement

Precise delivery dictates therapeutic and agronomic success. Ex vivo electroporation, nonviral LNPs, and AAV vectors dominate current pipelines; physical and peptide-based methods, virus-like particles, and engineered capsids expand tissue reach. Safety focuses on minimizing off-targets, large rearrangements, p53 activation, and immunogenicity. Unbiased detection (GUIDE-seq, DISCOVER-seq, CIRCLE-seq, long-read WGS) and functional assays quantify risk. In plants, transgene-free editing via RNP delivery and haploid induction reduces regulatory burden and gene flow concerns.

5. Ethics, Regulation, and Equitable Implementation

Clear boundaries around human germline editing, robust oversight of gene drives, and benefit-sharing frameworks are essential. Regulatory regimes increasingly distinguish transgene-free edits from transgenics, affecting approval pathways and labeling. Open science, responsible IP licensing, and capacity-building in low- and middle-income regions can mitigate inequities. Public engagement, transparent risk communication, and participatory governance are critical to legitimacy and trust.

Conclusion

CRISPR and genome editing are redefining the trajectories of agriculture and healthcare by coupling molecular precision with scalable translation. Technical refinements (base/prime editing, broadened PAMs, epigenome control) and maturing delivery methods underpin clinical and agronomic milestones, while rigorous safety profiling and measurement aim to de-risk deployment. The

transformative potential of editing—climate-resilient crops, curative somatic therapies—must be matched by ethical guardrails, equitable access, and adaptive regulation. With interdisciplinary stewardship, genome editing can advance food security and human health while honoring ecological integrity and societal values.

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