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CRISPR/Cas9 for Environmental Sustainability and Ecosystem Protection

Nurdana Salybekova[1*], Aikerim Serzhanova[1]

[1]*Department of Biology, Faculty of Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan*

*Corresponding Author e-mail: nurdana.salybekova@ayu.edu.kz

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Abstract

The development of CRISPR/Cas9 genome editing technology has revolutionized modern biotechnology, offering powerful tools not only for medicine and agriculture but also for addressing critical environmental challenges. This review examines recent advances in CRISPR/Cas9 technology with a particular focus on its applications in ecology and environmental sustainability. The use of CRISPR-based approaches enables the conservation of biodiversity through genetic rescue of endangered species and the control of invasive organisms that disrupt ecosystem balance. In addition, CRISPR/Cas9 has shown significant potential in environmental bioremediation by genetically enhancing microorganisms capable of degrading pollutants, including heavy metals, pesticides, and plastic waste. In agricultural ecosystems, genome editing contributes to the development of climate-resilient crops that reduce reliance on chemical inputs, thereby minimizing ecological damage to soil and water systems. The review also discusses ethical, ecological, and biosafety considerations associated with releasing gene-edited organisms into natural environments, emphasizing the need for robust regulatory frameworks. Overall, CRISPR/Cas9 represents a transformative technology for promoting ecosystem stability, environmental protection, and sustainable development under changing global conditions.

Cite

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INTRODUCTION

The rapid growth of the world's population may pose problems with food availability and health security. To maintain food security, crop yields must nearly double, and to achieve this goal, varieties that are resistant to various stresses must be developed *(*Adhikari & Poudel, 2020; Tester & Langridge, 2011*)*. Currently, CRISPR/Cas9 is the most widely used technology for creating models of human diseases, both in vitro, on different types of stem cells, and in vivo, on genetically modified animals *(Barrett, 2020)*.

The fast advancement of genome editing technology in recent years has revolutionized applied sciences and biological research. The CRISPR–Cas9 system is one of the most successful, straightforward, and affordable methods for precisely altering genetic material. Because of its adaptability, it is now a fundamental component of contemporary biotechnology, creating previously unheard-of possibilities in environmental sustainability, agriculture, and medicine. CRISPR-Cas9 has made it possible for researchers to investigate gene functions, comprehend the molecular causes of illnesses, and create novel treatment strategies for viral and hereditary diseases.

In the meantime, by increasing crop yield and resilience, this technology helps to improve global food security. These multidisciplinary uses show how genome editing can be used to address global food and health issues (Fontana et al., 2024; Ebina et al., 2013). Notwithstanding these developments, there are still issues with guaranteeing the morality, legality, and biosafety of genome editing. To fully utilize CRISPR-Cas9 for the good of humanity, ongoing international cooperation, open governance, and public knowledge are essential.

Medical and Clinical Applications of CRISPR-Cas9

One of the main applications of CRISPR-Cas9 is in medicine, where it is being actively used to study gene function and disease mechanisms. Genes that are important for the survival of cancer cells are being identified, as well as studied for therapies for various other diseases. By selectively modifying genes in human cells or model organisms, researchers can understand the underlying causes of genetic diseases (Fontana et al., 2024; Iyer et al., 2025; Lou et al., 2025; Sharma et al., 2023; Wei et al., 2023).

The creation of a CRISPR/Cas9-based method to interfere with integrated HIV-1 proviral DNA is another issue that Ebina et al. (2013) tackled. Their technique effectively cleaved and modified the viral genome by focusing on the LTRs, significantly decreasing LTR-driven expression and even removing internal viral genes from host chromosomes, indicating a possible treatment strategy for HIV-1 infection. According to Kolanu (2024), CRISPR/Cas9 gene editing has been successfully used to correct disease-causing mutations in several hereditary disorders, including sickle cell disease, cystic fibrosis, Duchenne muscular dystrophy, and retinitis pigmentosa, and is being clinically tested for conditions such as β-thalassemia and Leber congenital amaurosis.

In order to address hereditary blood illnesses, recent developments in CRISPR–Cas9 technology have made it possible to precisely modify hematopoietic genes. CRISPR-Cas9-mediated editing of the HBG1 and HBG2 promoters was effectively demonstrated by Sharma et al. (2023), providing an efficient treatment strategy for β-thalassemia and sickle cell disease.

Wei et al. (2023) showed that a single local ocular injection of HSV-1-targeting CRISPR accomplished viral suppression without apparent off-target effects or systemic side events, demonstrating the clinical promise of in vivo CRISPR–Cas9 gene editing for the treatment of herpetic stromal keratitis. Their results demonstrate the wider potential of direct ocular gene editing for the treatment of immune-mediated and viral ocular disorders.

Lou et al. (2025) conducted the first-in-human trial using CRISPR–Cas9 to disrupt the intracellular immune checkpoint gene CISH in tumor-infiltrating lymphocytes from patients with metastatic gastrointestinal epithelial cancers, including colorectal cancer, demonstrating the clinical viability of CRISPR-edited T cells for cancer immunotherapy.

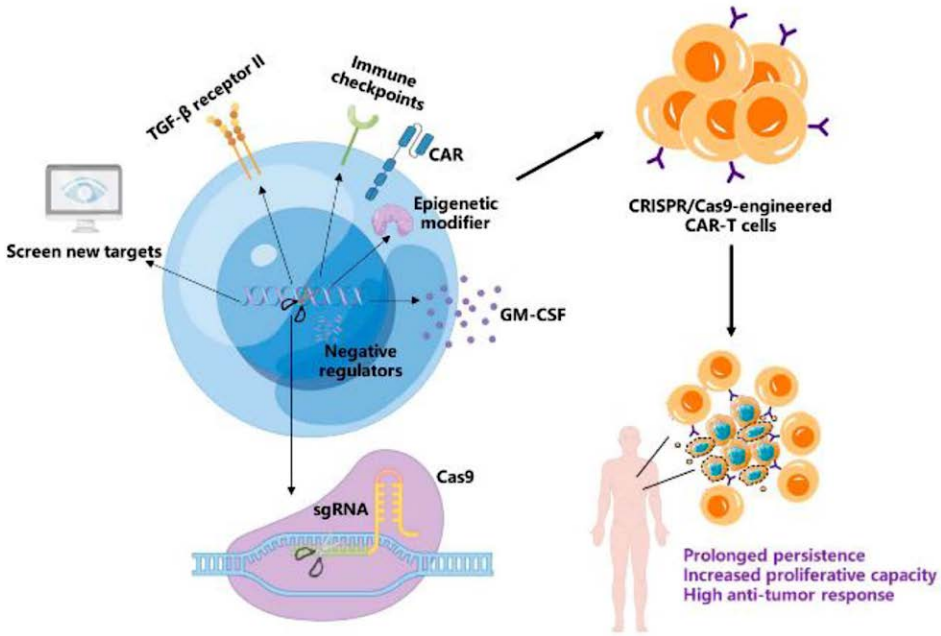

Fig. 1. A schematic of applications of CRISPR/Cas9 technology in CAR-T cells to improve long-term persistence (Wei et al., 2023)

Similarly, CTX130, a CD70-targeted CRISPR-engineered CAR-T cell treatment, demonstrated encouraging safety and efficacy in patients with relapsed or refractory T-cell malignancies, according to Iyer et al. (2025). Collectively, these results demonstrate the growing contribution of CRISPR-based strategies to the development of customized immunotherapy and oncology.

The therapeutic potential of CRISPR–Cas9 in immune cell engineering was demonstrated by Wang et al. (2024) in a seminal work on allogeneic CD19 CAR-T treatment for patients with severe autoimmune disorders. Together, these immunologic and oncologic studies provide credence to CRISPR's versatility in reprogramming immune cells for a range of therapeutic uses (Fig.1). These results collectively show how gene editing might alter immune responses, fix genetic abnormalities, and open the door to novel approaches to treating complicated illnesses.

In conclusion, the reprogramming of immune cells using CRISPR-Cas9 represents a major advancement in immunology and oncology. The results of the study show that CRISPR-based genome editing can improve therapeutic precision, restore disease-causing mutations, and modify immune responses. These discoveries show how CRISPR-engineered immune cells have the potential to revolutionize the way autoimmune, hematological, and oncological illnesses are treated, bringing in a new era of cell-based and customized medicine.

Applications in Molecular and Agricultural Sciences

CRISPR-Cas9 technology offers significant opportunities for the development of agriculture. CRISPR-Cas9 technology can solve global food security problems. By modifying crop genomes, it is possible to grow varieties that are more resistant to pests, diseases, and environmental stresses, thereby increasing productivity and reducing crop losses (Fig.2). Pal et al. (2025) claim that

CRISPR/Cas-mediated genome editing makes it possible to directly alter genes related to nutrient production, accumulation, and metabolic control in horticulture crops. CRISPR can dramatically raise levels of vitamins, minerals, antioxidants, and other health-promoting substances by precisely removing negative regulators or turning on important biosynthesis genes. The production of nutrient-dense crops that can lessen micronutrient deficits and boost human health is made possible by this gene-targeted improvement.

Genetic and molecular breeding have made it possible to create genetic combinations from multiple species, resulting in increased productivity of transgenic crops.

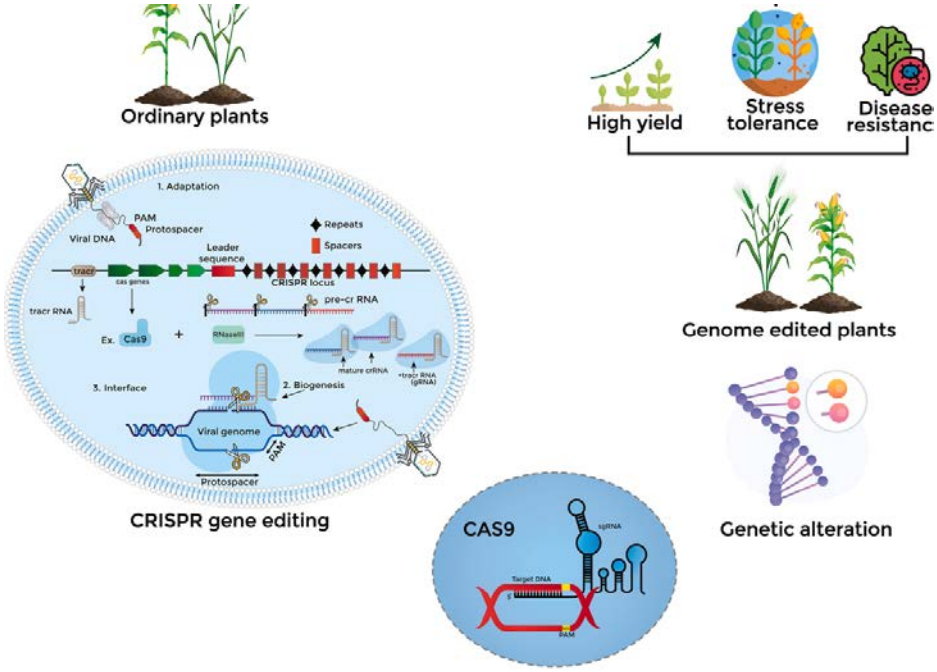

Fig. 2. CRISPR-Enabled applications in molecular and agricultural sciences (Muha-Ud-Din et al., 2024)

Although the application of CRISPR-Cas9 in agriculture has great potential, it is not without challenges. Regulatory frameworks and public acceptance remain important factors, particularly regarding genetically modified organisms (GMOs) (Kuprešanin et al., 2025). Chen et al. (2023) characterized acetyltransferase-mediated detoxifying pathways to show how gene editing can be used to improve herbicide tolerance in rice. This work demonstrates how focused gene editing can increase crop tolerance and decrease reliance on chemicals, so promoting more environmentally friendly farming methods.

The most common abiotic stresses threatening agriculture are elevated temperatures, drought, salinity, and heavy metal pollution. Many genes involved in plant responses to abiotic stress are now known, and the development of CRISPR/Cas technology has made it possible to manipulate many of them. Knockout of the ARF4 gene improved water uptake efficiency in tomato plants, resulting in plants with greater tolerance to salinity and osmotic stress (Bouzroud et al., 2020). The CRISPR/Cas system is a cutting-edge tool for knocking out genes that negatively affect plant yield. According to Cui et al. (2020), CRISPR/Cas9 knockout of gs3 and dep1 markedly improved salinity

tolerance. Under salt-stress conditions, the gs3 mutant showed a ~1.6-fold increase in survival, while the dep1 mutant demonstrated a ~1.7-fold increase compared with the wild type.

Currently, efforts are being made to resolve present issues and provide precise rules for the ethical application of CRISPR-Cas9 in agriculture. This technology has the ability to transform agricultural practices and fortify a resilient and sustainable global food system as research advances and regulatory frameworks change. CRISPR–Cas9 has the potential to greatly improve global food security by enhancing crop metabolic pathways and creating cultivars that are resistant to pests, diseases, and environmental stressors. Furthermore, food safety and ecological stability will be guaranteed by its responsible use, which is in line with biosafety and ethical norms. In the end, combining gene editing technologies like CRISPR-Cas9 is a revolutionary step toward attaining environmental sustainability and agricultural productivity.

Ethics, and Future Perspectives

The rapid development of CRISPR-Cas9 applications in medicine, agriculture, and biotechnology is accompanied by concerns about biosafety. In particular, the precise and safe application of genome editing components to a subject requires the optimization of the strategy for the new technology.

Current innovations in system-based approaches have focused largely on lipid nanoparticles and mRNA-based CRISPR platforms. These methods seek to reduce immunogenicity and increase accuracy. Ex vivo procedures give greater control and safety during genetic manipulation, whereas in vivo approaches offer broader systemic applications, according to comparative research comparing the two types of editing.

CRISPR research continues to be driven by ethical and regulatory issues. Clinical trials must take patient safety, preventing off-target mutations, and long-term monitoring into account. In order to ensure adherence to Good Clinical Practice (GCP) guidelines and ongoing ethical assessment during development, the U.S. Food and Drug Administration (FDA) has created frameworks for assessing genome editing medicines. To strike a balance between innovation and responsibility, transparent governance and international cooperation are essential.

Artificial intelligence (AI) integration for guide RNA creation, off-target effect prediction, and gene-editing outcome optimization are prospects for CRISPR technology. Moreover, agricultural biotechnology and customized medicine stand to benefit greatly from the conversion of molecular genetic research into large-scale biomanufacturing. The long-term societal impact and sustainability of CRISPR tools will depend on how ethically they are implemented as they advance in accuracy and safety.

DISCUSSION

The rapid advancement of research on the CRISPR–Cas9 system has had a significant impact on medicine, agriculture, and biotechnology. The reviewed studies show that the CRISPR genome-editing method requires high precision and in-depth research to correct disease-causing mutations and produce plant species resistant to biotic factors. Clinical trials in medicine and agricultural agrobiotechnology studies have proven that genome editing is one of the most effective new technologies.

Further research is needed to identify new target genes for genome editing and to explore unexplored clinical, metabolic pathways that could be used for such enhancement. The

CRISPR/Cas9 genome editing tool is characterized by high efficiency, user-friendliness, and precise targeting.

Comprehensive genomic and transcriptome investigations, along with bioinformatic modeling, are required to identify new targets for genome editing. These methods enable us to pinpoint the exact genes involved in the onset of specific illnesses or in the control of metabolic processes. It is important to consider the CRISPR/Cas9 system's off-target impacts and ethical concerns in addition to its benefits. Future studies should focus on lowering these restrictions, enhancing system accuracy, and creating next-generation editing platforms (such base or prime editing, CRISPR/Cas12, etc.).

CONCLUSION

Recent developments in CRISPR-Cas9 research have validated the technology's potential as a potent, accurate, and effective genome editing tool. The technology is more accurate and versatile than previous gene-editing methods, and clinical and pre-clinical investigations continue to confirm its therapeutic safety and efficacy. Modern biotechnology is further strengthened by the technology's high efficiency, clinical viability, and the increasing clarity of international regulatory frameworks.

However, there are still a few restrictions. The potential for causing unwanted genetic modifications and off-target mutations presents serious ethical and biosafety issues. Furthermore, inconsistent national regulatory frameworks continue to impede the widespread adoption of CRISPR-based advancements in clinical or agricultural settings.

In the future, it will be crucial to ensure that CRISPR technologies are applied sensibly and ethically, striking a balance between innovation and social benefits, safety, and accessibility. Through open international cooperation and thorough monitoring, CRISPR-Cas9 can continue to evolve into a transformative technology that benefits human health, sustainability, and scientific advancement.

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