CRISPR-Cas9 in Agriculture: Advancements and Perspectives

NIYORUGIRA SEBIGUNDA Jackson [*]
BALUME KAYANI Isaac [**]

Abstract

The CRISPR-Cas9 system has emerged as one of the most transformative genome-editing technologies, offering unprecedented precision, efficiency, and versatility in modifying genetic material. In agriculture, it provides innovative solutions to critical global challenges, including food insecurity, climate change, pest and disease outbreaks, and the increasing demand for sustainable food production. This review examines the molecular mechanism of CRISPR-Cas9 and its diverse applications in crop and livestock improvement. In crop breeding, the technology has enabled the development of high-yielding, disease-resistant, drought-tolerant, and nutritionally enhanced varieties while significantly reducing the time required for conventional breeding. In livestock, CRISPR-Cas9 has been applied to improve disease resistance, productivity, reproductive performance, and animal welfare. The review also highlights recent advances, including base editing, prime editing, multiplex genome editing, and the integration of CRISPR with genomics and phenomics, which have expanded its precision and practical applications. Despite these remarkable achievements, challenges related to biosafety, ethical concerns, public acceptance, intellectual property, and regulatory frameworks continue to influence its adoption. Overall, CRISPR-Cas9 represents a powerful tool for accelerating agricultural innovation and supporting sustainable farming systems. Continued research, responsible governance, and international collaboration will be essential to ensure its safe, equitable, and effective contribution to global food security and agricultural resilience.

Keywords: *CRISPR-Cas9, Agriculture.*

Résumé

Le système CRISPR-Cas9 est devenu l'un des outils de modification génétique les plus révolutionnaires, nous offrant une précision, une efficacité et une flexibilité inégalées pour

[*] *Faculty of Agronomy and Environment,* ***University of Goma****, DRC; Institut National d'Étude et de Recherche Agronomiques, Station de Masisi, DRC ; Centre de Recherche sur le Développement Durable et Société, RDC ; Corresponding e-mail : jacksonsebigunda@unigom.ac.cd, ORCID ID Sebigunda J.N. : https://orcid.org/0009-0002-1901-4974 ;*

*** *Faculty of Agronomy and Environment,* ***University of Goma****, DRC; ORCID ID Balume K. I : https://orcid.org/0009-0003-4749-8352 Tel : +243 998 967 450 , +243 993 744 363.*

modifier le matériel génétique. Dans l’agriculture, il propose des solutions intelligentes à des problèmes mondiaux majeurs comme la pénurie alimentaire, le changement climatique, les épidémies de maladies et de parasites, et le besoin croissant de production alimentaire durable. Cette revue examine comment CRISPR-Cas9 fonctionne au niveau moléculaire et ses nombreuses applications pour améliorer les cultures et le bétail. Pour l’amélioration des cultures, cette technologie a permis de créer des variétés à haut rendement, résistantes aux maladies, tolérantes à la sécheresse et plus nutritives, tout en réduisant le temps nécessaire par rapport à la sélection traditionnelle. Pour le bétail, CRISPR-Cas9 est utilisé pour renforcer la résistance aux maladies, la productivité, la reproduction et le bien-être général des animaux. La revue met également en avant les progrès récents, y compris l'édition de bases, l'édition prime, l'édition génomique multiple et l'intégration du CRISPR avec la génomique et la phénotypique, qui ont élargi sa précision et ses applications pratiques. Malgré ces réalisations remarquables, des défis liés à la biosécurité, aux préoccupations éthiques, à l'acceptation par le public, à la propriété intellectuelle et aux cadres réglementaires continuent d'influencer son adoption. Dans l'ensemble, le CRISPR-Cas9 représente un outil puissant pour accélérer l'innovation agricole et soutenir des systèmes agricoles durables. La poursuite de la recherche, une gouvernance responsable et la collaboration internationale seront essentielles pour assurer sa contribution sûre, équitable et efficace à la sécurité alimentaire mondiale et à la résilience agricole.

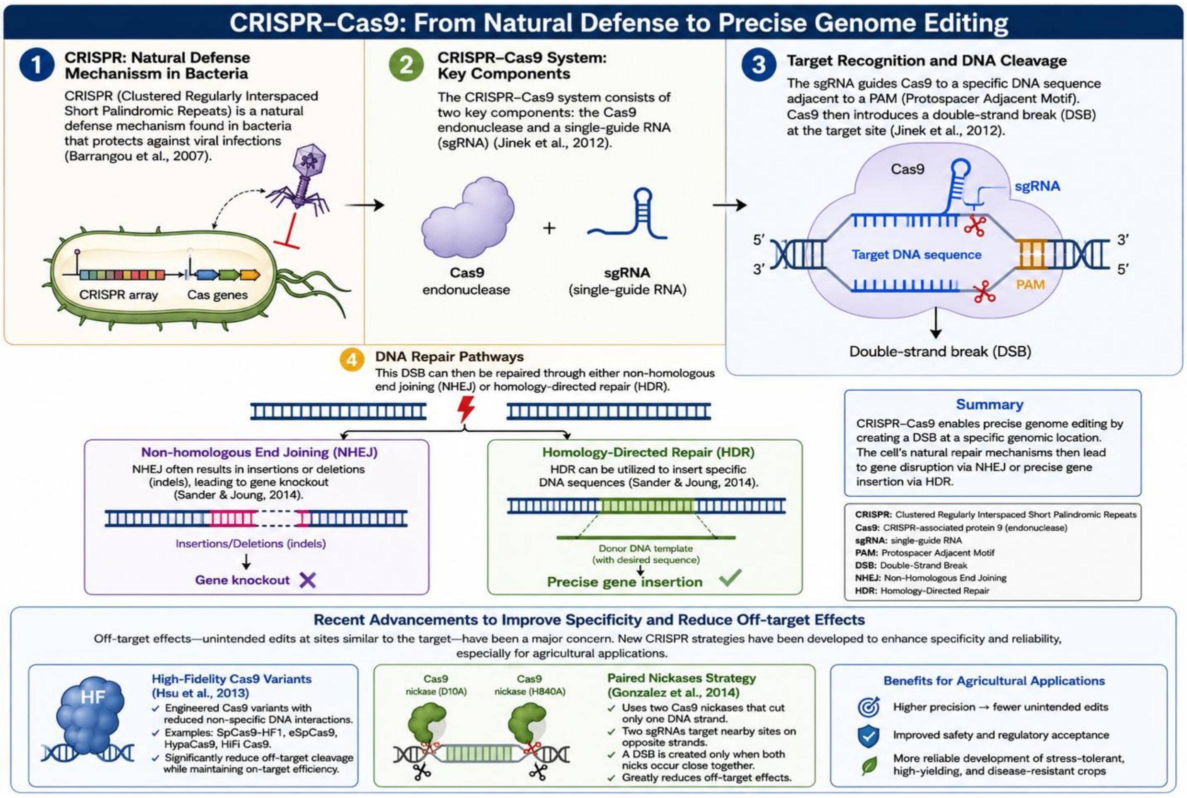
Mots-clés : *CRISPR-Cas9, Agriculture.*

I. Introduction

Agriculture faces significant challenges in meeting the demands of a growing global population, projected to reach nearly 10 billion by 2050 (United Nations, 2022). Issues such as climate change, soil degradation, and increasing pest resistance threaten food production systems worldwide (Godfray et al., 2010). Traditional breeding methods, while effective, often require extended timeframes and limited genetic diversity (McCouch et al., 2013). The advent of CRISPR-Cas9 gene editing technology provides a transformative approach to agricultural biotechnology, enabling precise modifications to plant and animal genomes (Jinek et al., 2012). This review discusses the underlying mechanisms of

CRISPR-Cas9, its diverse applications in agriculture, recent advancements in the field, and the ethical implications surrounding its deployment.

II. Mechanism of CRISPR-Cas9



CRISPR (*Clustered Regularly Interspaced Short Palindromic Repeats*) is a natural defense mechanism found in bacteria that protects against viral infections (Barrangou et al., 2007).

The CRISPR-Cas9 system consists of two key components: the Cas9 endonuclease and a single-guide RNA (sgRNA). The sgRNA guides Cas9 to a specific DNA sequence, where Cas9 introduces a double-strand break (DSB) (Jinek et al., 2012). This DSB can then be repaired through either non-homologous end joining (NHEJ) or homology-directed repair (HDR). NHEJ often results in insertions or deletions (indels), leading to gene knockout, while HDR can be utilized to insert specific DNA sequences (Sander & Joung, 2014).

Figure 1. CRISPR-Cas9 from natural Defense to Precise Genome Editing

Enhanced Specificity and Precision

Recent advancements in CRISPR technology have focused on enhancing specificity and reducing off-target effects, which have been a concern in earlier applications. Techniques such as high-fidelity Cas9 variants (Hsu et al., 2013) and paired nickases (Gonzalez et al.,

2014) have been developed to minimize unintended edits, thereby improving the reliability of gene editing in agricultural applications. **(See Figure 2)**

Applications in Agriculture

Crop Improvement: CRISPR-Cas9 technology has been utilized to enhance various agronomic traits in crops, including:

Disease Resistance: Gene editing has been used to confer resistance against pathogens. For instance, CRISPR-Cas9 has been employed to enhance resistance to rice blast disease by targeting specific susceptibility genes (Xiang et al., 2019). Similar approaches have been applied to other crops, demonstrating the potential to reduce reliance on chemical pesticides and improve crop yield (Zhou et al., 2020). **(See Figure 3 & 4)**

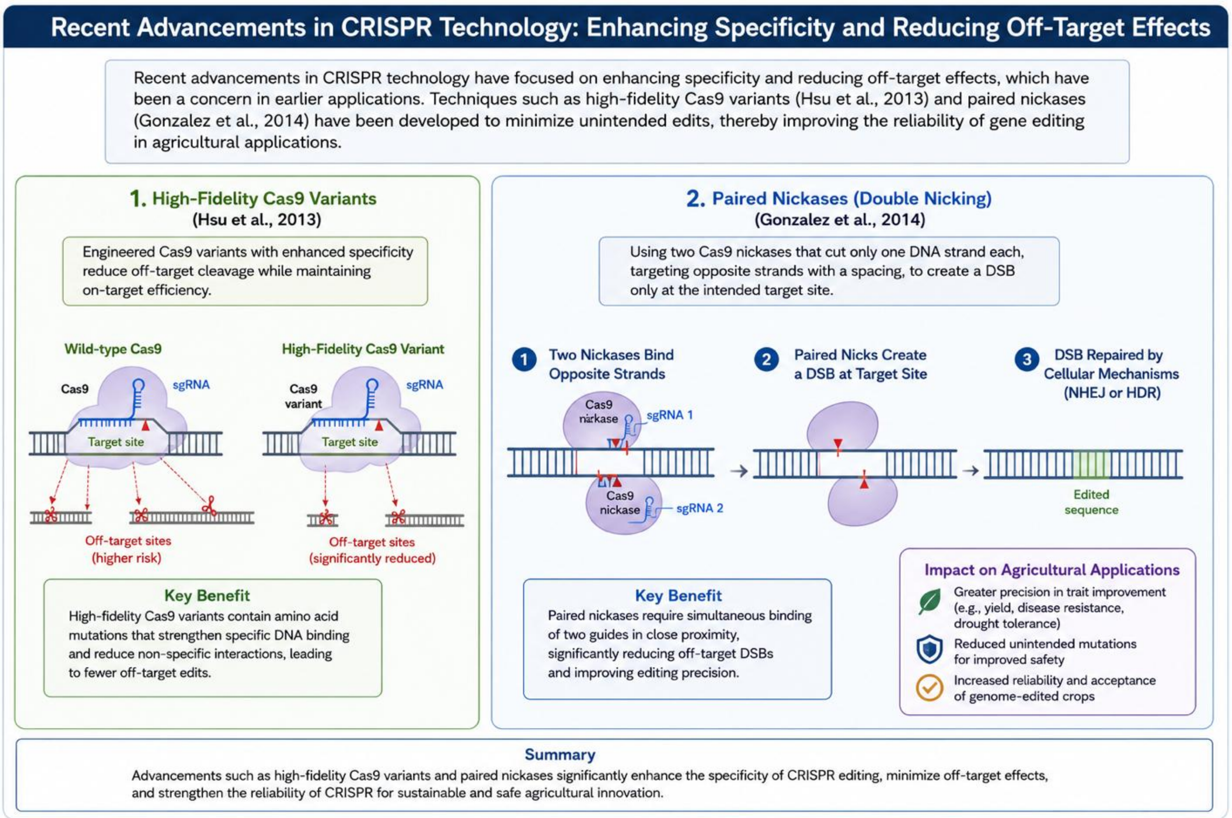


Figure 2. Recent advancement in CRISPR Technology

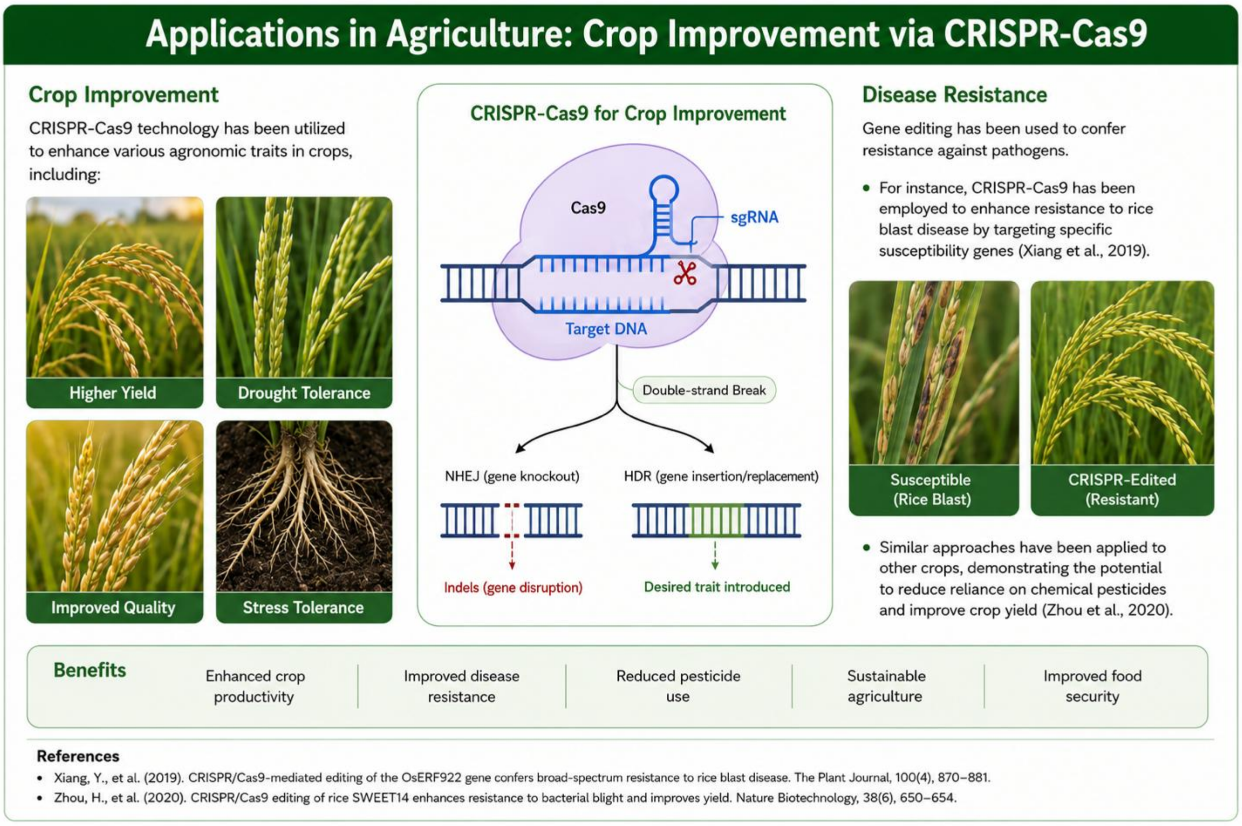


Figure 3. Recent advancement in CRISPR Technology

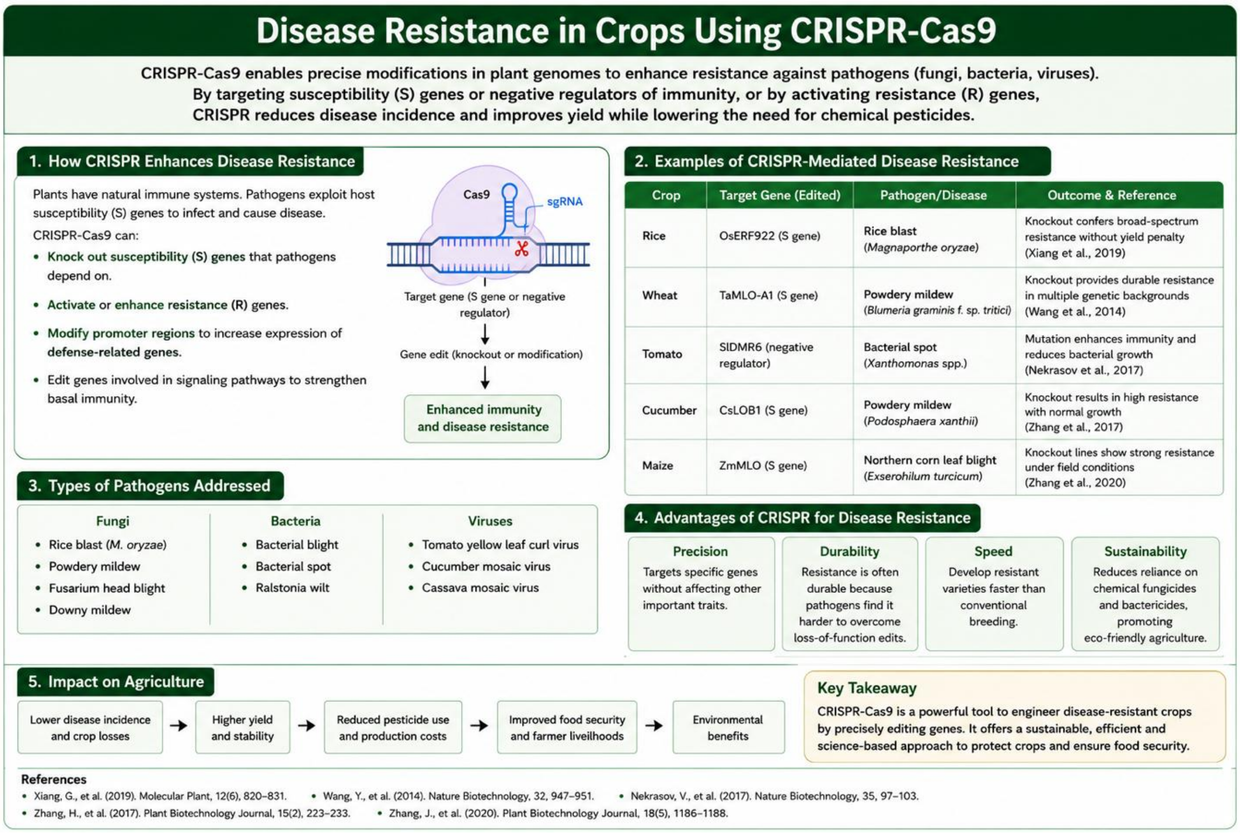


Figure 4. Disease Resistance in Crops using CRISPR Cas-9

Abiotic Stress Tolerance: Researchers have targeted genes involved in drought and salinity tolerance. For example, modifying the gene OsDREB2A in rice improved tolerance to drought stress, leading to increased yield under water-limited conditions (Jiang et al., 2019). Furthermore, CRISPR has been used to enhance salt tolerance in various crops by targeting specific transport genes, enabling cultivation in saline soils (Zhang et al., 2021). **(See Figure 5)**

Nutritional Quality: CRISPR-Cas9 has been utilized to enhance the nutritional profile of crops. The editing of genes involved in beta-carotene biosynthesis in rice has led to the development of biofortified varieties, such as Golden Rice (Ye et al., 2000). In addition, gene editing has been applied to enhance the protein content in legumes, contributing to improved dietary quality (Liu et al., 2020). **(See Figure 6)**

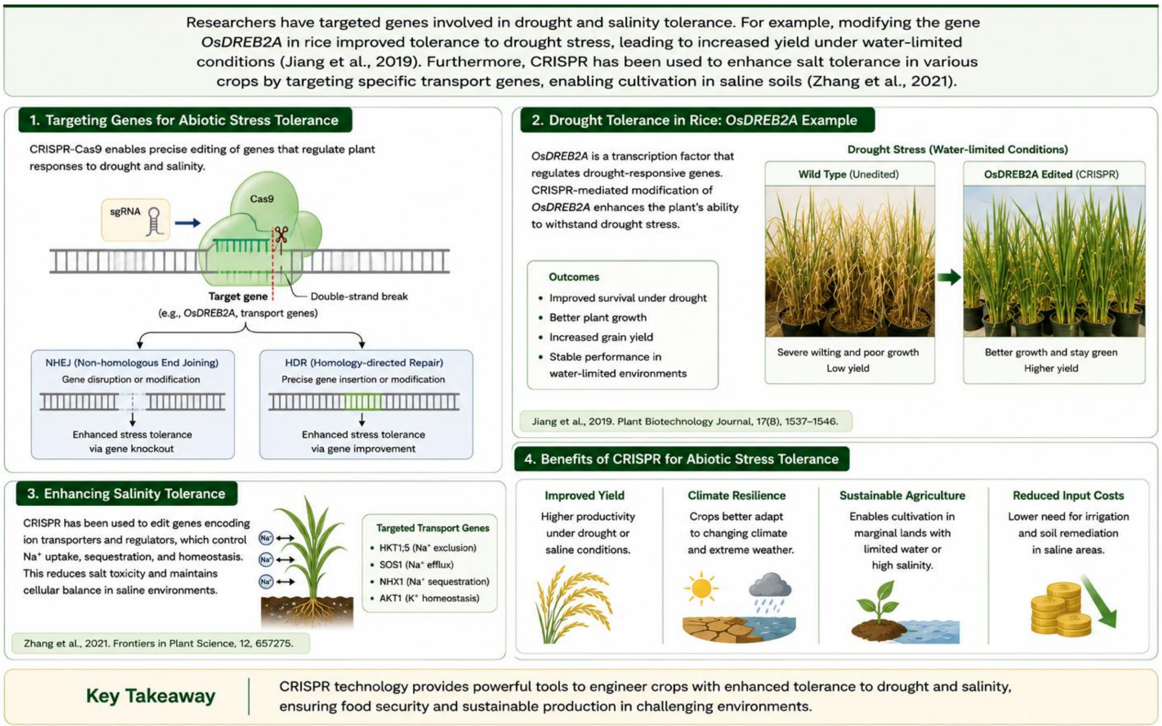


Figure 5. Abiotic Stress Tolerance using CRISPR Cas-9

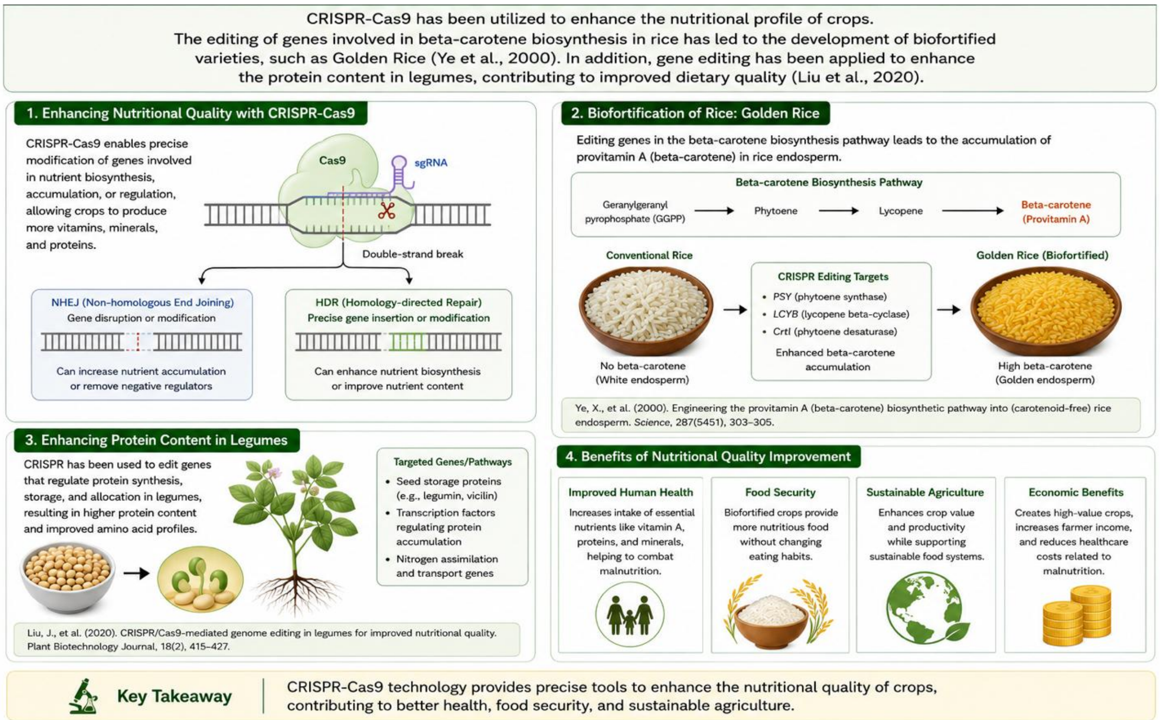


Figure 6. Nutritional quality improvement using CRISPR Cas-9

Livestock Improvement: CRISPR-Cas9 technology also holds promise in livestock breeding. Applications include:

Disease Resistance: Gene editing can enhance disease resistance in livestock. For instance, the deletion of the CD163 gene in pigs renders them resistant to the Porcine Reproductive and Respiratory Syndrome Virus (PRRSV) (Niu et al., 2015). Similar strategies have been applied to improve resistance to diseases in cattle and poultry, highlighting the potential to reduce veterinary costs and improve animal welfare (Wang et al., 2018).

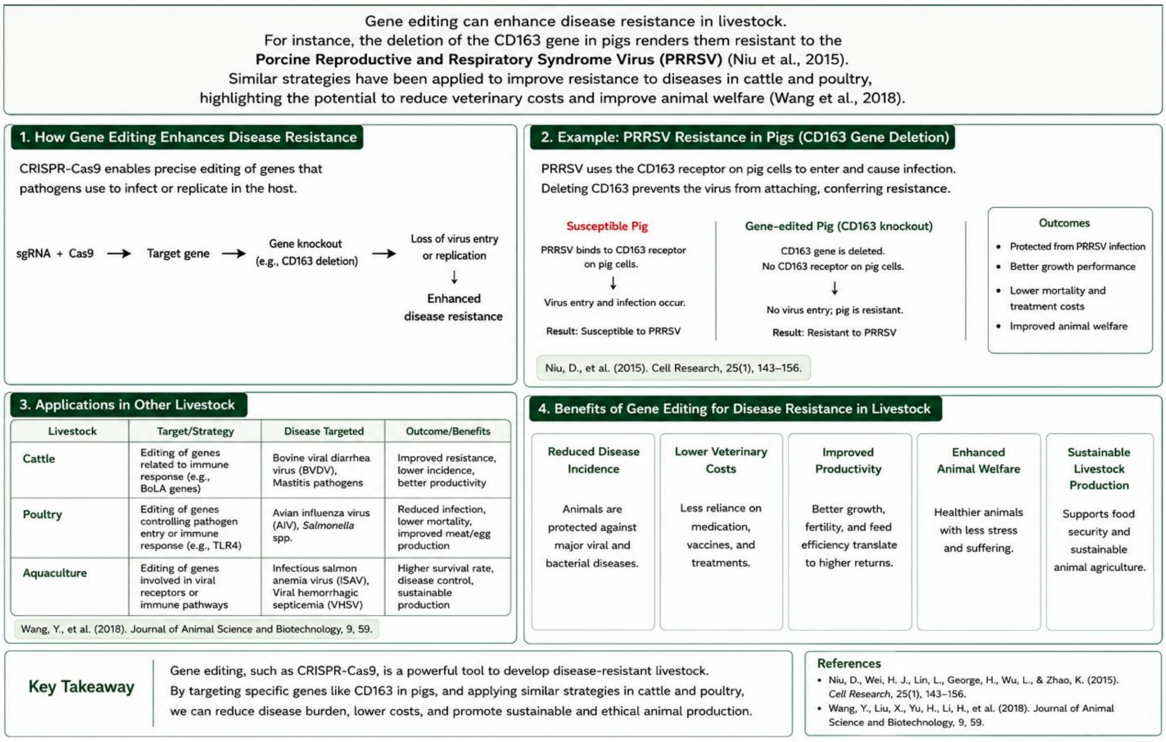


Figure 7. Disease resistance in Livestocks

Improved Production Traits: Researchers have targeted genes that influence growth rates and feed efficiency, potentially leading to livestock that require fewer resources and produce more meat or milk (Zhao et al., 2020). Gene editing has also been employed to enhance the quality of meat and dairy products, addressing consumer demand for healthier options (Mellor et al., 2020). **(See figure 8)**

Recent Advancements: Recent advancements in CRISPR-Cas9 technology have significantly enhanced its applicability in agriculture:

Multiplex Editing: The development of multiplex CRISPR systems allows for the simultaneous editing of multiple genes, enabling the simultaneous enhancement of several traits in a single organism (Kakumanu et al., 2019). This capability can expedite the development of crops with multiple desirable traits, such as disease resistance and improved yield.

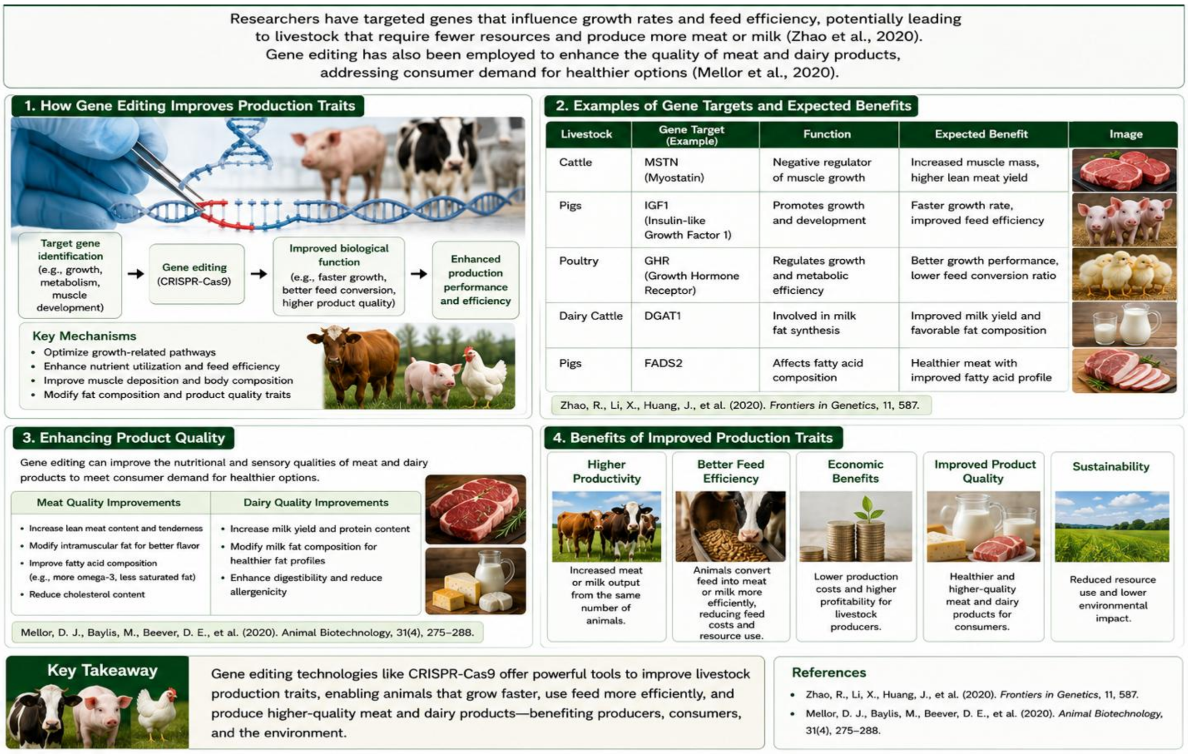


Figure 8. Improved Production Traits using CRISPR-Cas9

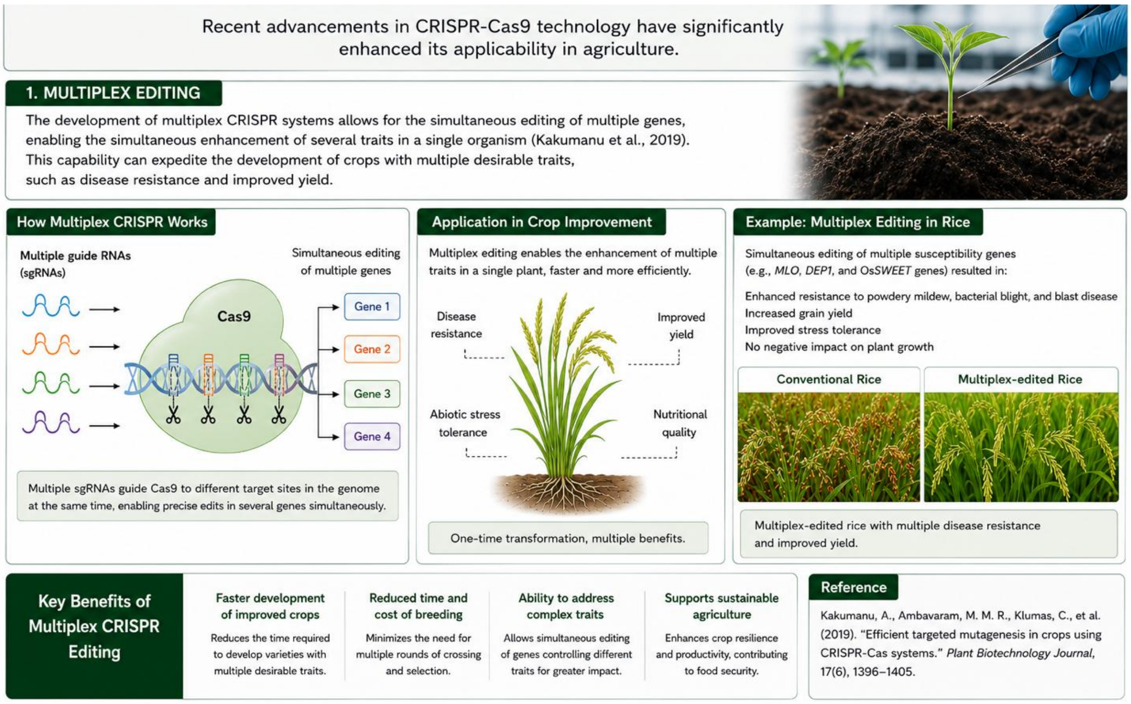


Figure 9. Multiplex editing using CRISPR Cas9

Base Editing: This novel technique allows for precise nucleotide changes without causing DSBs, reducing the risk of unintended mutations (Komor et al., 2016). Base editing has been utilized in various crops to achieve desired traits more efficiently, providing a powerful tool for plant breeders (He et al., 2019). **(See Figure 10)**

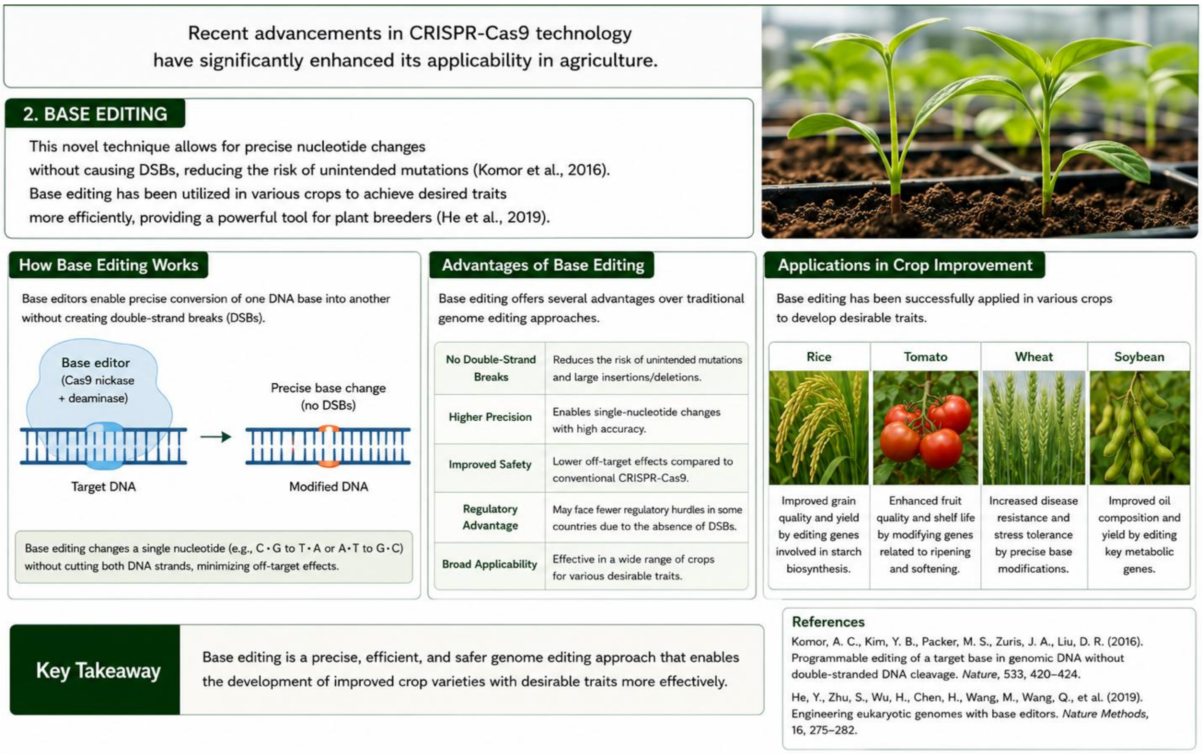


Figure 10. Base Editing using CRISPR Cas9

Delivery Systems: Advances in delivery methods, including nanoparticles and agrobacterium-mediated transformation, have improved the efficiency of CRISPR-Cas9 applications in crops and livestock (Zhang et al., 2021). Improved delivery systems enhance the stability and uptake of CRISPR components, increasing the likelihood of successful gene editing. **(See Figure 11)**

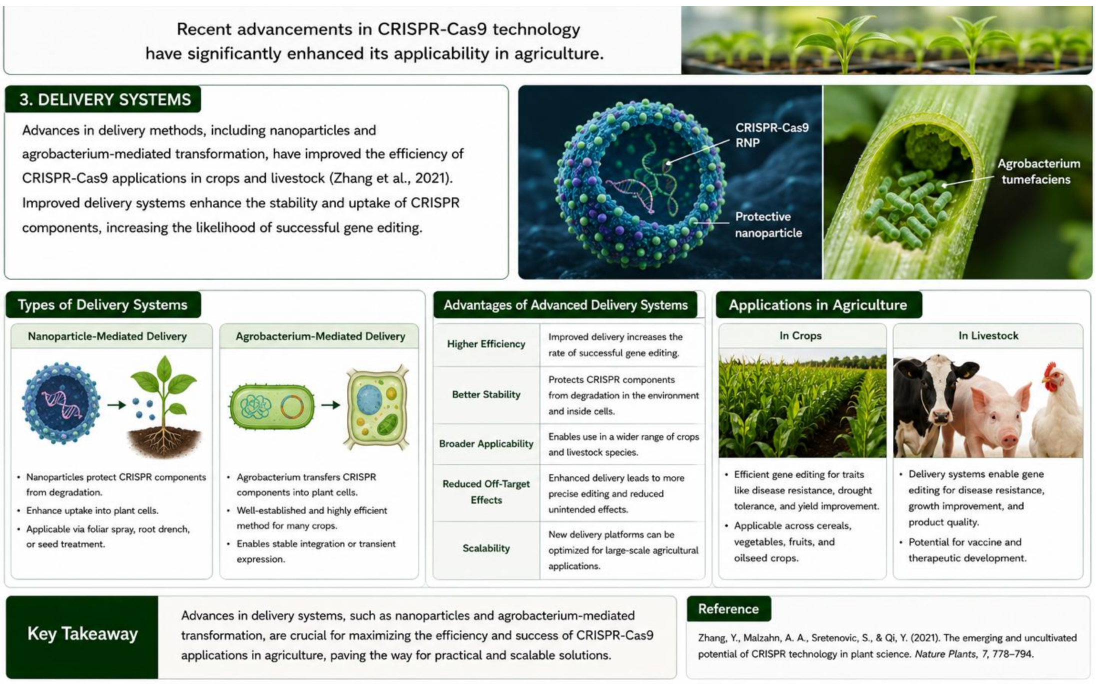


Figure 11. Delivery system using CRISPR Cas9

Challenges and Ethical Considerations: Despite the promise of CRISPR-Cas9 technology, several challenges and ethical considerations remain:

Regulatory Frameworks: The regulatory status of CRISPR-edited organisms varies globally, creating uncertainty for developers and farmers (Nuffield Council on Bioethics, 2016). Some countries treat gene-edited crops similarly to genetically modified organisms (GMOs), necessitating extensive regulatory oversight (Wolt et al., 2016). This inconsistency can hinder innovation and the adoption of CRISPR technology in agriculture. **(See Figure 12)**

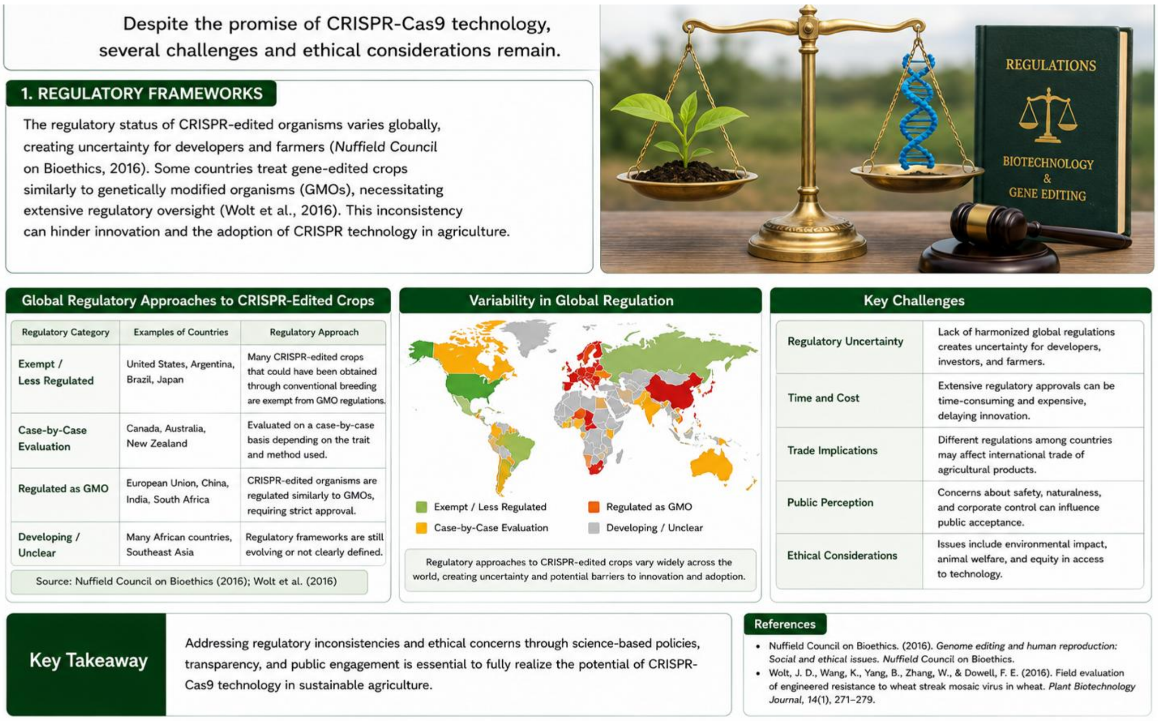


Figure 12. Regulatory status of CRISPR-edited organisms

Biodiversity Concerns: There is concern that widespread use of gene editing could reduce genetic diversity in crops and livestock, potentially increasing vulnerability to diseases and pests (García et al., 2019). Maintaining genetic diversity is crucial for ensuring the resilience of agricultural systems in the face of changing environmental conditions (Meyer et al., 2016). **(See Figure 13)**

Ethical Implications: The ability to edit the genomes of living organisms raises ethical questions regarding the manipulation of life and the potential for unintended consequences in ecosystems (Lemaire, 2018). Public perception of gene editing technologies can influence regulatory decisions and the acceptance of CRISPR in agricultural practices (Miller et al., 2016).

Future Perspectives: The future of CRISPR-Cas9 in agriculture appears promising. Ongoing research aims to refine editing techniques, enhance precision, and develop crops and livestock that can thrive in a changing climate. Collaboration between scientists, policymakers, and the public will be essential to navigate the ethical and regulatory landscapes associated with this technology. **(See Figure 14)**

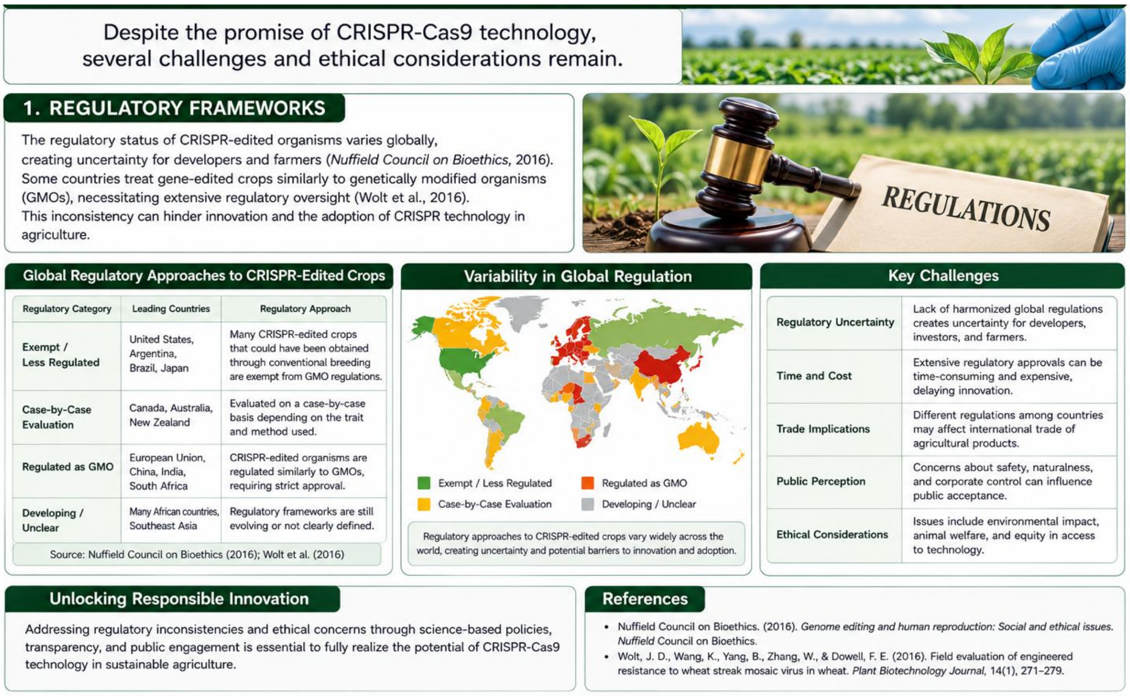


Figure 13. Regulatory frameworks for CRISPR-edited organisms

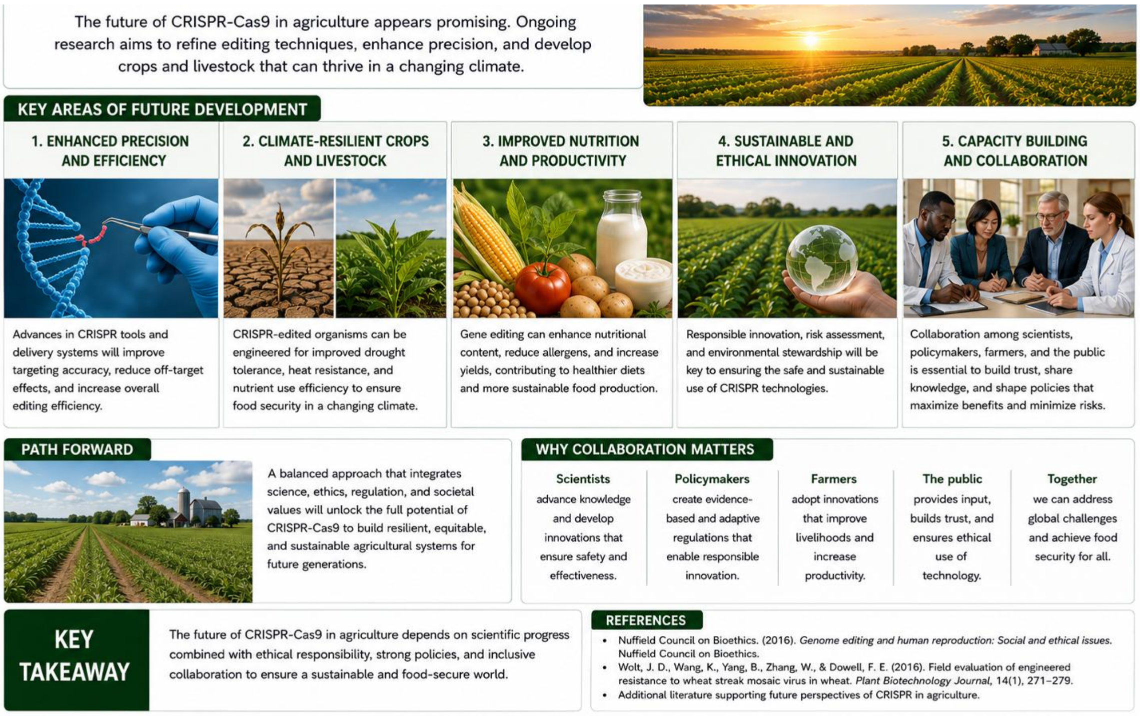


Figure 14. Future of CRISPR-Cas9 in agriculture

Integration with Other Technologies: Combining CRISPR-Cas9 with other biotechnological advancements, such as genomics and phenomics, can enhance the efficiency of trait selection and breeding programs (Zhang et al., 2018). Integrating these technologies may lead to more rapid advancements in developing resilient crops and livestock.

Global Collaboration: International collaboration in research and development can accelerate the adoption of CRISPR technology in agriculture (Huang et al., 2018). Establishing global networks for knowledge sharing and best practices will be crucial for addressing food security challenges. **(See Figure 15)**

1. INTEGRATION WITH OTHER TECHNOLOGIES

Combining CRISPR-Cas9 with other biotechnological advancements, such as genomics and phenomics, can enhance the efficiency of trait selection and breeding programs (Zhang *et al.*, 2018). Integrating these technologies may lead to more rapid advancements in developing resilient crops and livestock.

Technology Combination	Expected Benefit
Genomics + CRISPR-Cas9	Understanding genetic variation and potential
Phenomics + CRISPR-Cas9	High-throughput trait measurement
CRISPR-Cas9 (Advanced Editing)	Precise and efficient gene editing
Integration Outcome	Resilient, high-yielding, and nutritious varieties

Integrated technologies accelerate innovation and improve the efficiency of agricultural development.

2. GLOBAL COLLABORATION

International collaboration in research and development can accelerate the adoption of CRISPR technology in agriculture (Huang *et al.*, 2018). Establishing global networks for knowledge sharing and best practices will be crucial for addressing food security challenges.

Key Areas of Collaboration	Contribution to Food Security
Knowledge Sharing	Exchange of research findings, data, and technologies across borders.
Capacity Building	Training researchers and strengthening laboratories and institutions worldwide.
Best Practices	Developing and promoting ethical, safe, and effective applications.
Joint Research & Innovation	Collaborative projects to solve common agricultural and food security challenges.

Global collaboration accelerates innovation, ensures responsible use, and helps achieve sustainable food security for all.

Figure 15. International collaboration in research and development can accelerate the adoption of CRISPR

Conclusion

CRISPR-Cas9 technology represents a revolutionary advancement in agricultural biotechnology, providing innovative solutions to some of the most pressing challenges affecting global food production. Its remarkable precision, efficiency, and flexibility enable targeted genetic improvements that can enhance crop resilience to pests, diseases, drought, and other environmental stresses while increasing yield and nutritional quality. In livestock, CRISPR-Cas9 offers opportunities to improve disease resistance, productivity, reproductive performance, and animal welfare, contributing to more sustainable and efficient farming systems. By accelerating breeding programmes and reducing dependence on chemical inputs, this technology supports environmentally friendly agricultural practices and strengthens global food security. However, its successful adoption depends on addressing critical challenges, including biosafety concerns, ethical considerations, regulatory frameworks, intellectual property issues, and public acceptance. Transparent governance, rigorous risk assessment, and international collaboration are essential to ensure its responsible application. With continued scientific innovation and appropriate policies, CRISPR-Cas9 has the potential to transform agriculture and promote resilient, sustainable food systems for future generations.

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