
**INTERNATIONAL JOURNAL OF CURRENT RESEARCH IN
CHEMISTRY AND PHARMACEUTICAL SCIENCES**

ISSN: 2348-5213 (Print), ISSN: 2348-5221 (Online)

www.ijcrcps.com

(A Peer Reviewed, Referred, Indexed and Open Access Journal)

DOI: 10.22192/ijcrcps

Coden: IJCROO(USA)

Volume 13, Issue 9- 2026

Review Article



DOI: <http://dx.doi.org/10.22192/ijcrcps.2026.13.09.002>

Application of CRISPR-Cas9 technology in animal production improvement and product industry

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Abstract

Genomic selection and CRISPR-Cas9 gene-editing technologies have brought advances in animal breeding to a new level. Genomic selection has facilitated forecasting the breeding values on the basis of genome wide markers, which enhances more accuracy and effectiveness in choosing the best animals in terms of production, health and reproduction traits. CRISPR-Cas9 technology on the other hand has brought about a revolution in genetic modification in that it enables specific and inexpensive and precise genome editing. Animals occur via modification of the zygote, accompanying the areas which include disease resistance, reproductive health enhancement, productivity enhancement, and product quality improvement. A thorough analysis of previous research highlights the potential of CRISPR-Cas9 in overcoming genetic disorders by targeting specific mutations in genes. Furthermore, its integration with reproductive biotechnologies and genomic selection facilitates the production of gene-edited animals with high genomic value, contributing to genetic enhancement and improved productivity. Additionally, CRISPR-Cas9 opens new avenues for developing disease-resistant livestock and creating innovative breeding models for high-quality production. A key trend in the field is the development of multi-sgRNA vectors to correct mutations in various genes linked to productivity traits or certain diseases within individual genomes, thereby increasing resistance in animals. However, despite the potential advantages of CRISPR-Cas9, public acceptance of genetically modified agricultural products remains uncertain. Therefore Continued advancements in this technology and its underlying mechanisms promise to improve poultry products and genetically modified livestock. Overall, CRISPR-Cas9 technology offers a promising pathway for advancing livestock breeding practices, with opportunities for genetic improvement, enhanced disease resistance, and greater productivity.

Keywords: CRISPR-Cas9, Application, livestock, Improvement, Production

1. Introduction

Genomics have been evolving and advancing for many decades since its origin, but the last decade has witnessed a breakthrough technology known as clustered regularly interspaced short palindromic repeats (CRISPR)-cas9 technology, which has the potential to revolutionize the genomics and gene editing technologies (Zhu *et al.*, 2022). The rapid development of genome-editing technologies has profoundly reshaped modern animal science, with CRISPR–Cas9 standing at the forefront of this transformation which adapted from a bacterial adaptive immune system, CRISPR–Cas9 offers a programmable and highly efficient mechanism for inducing targeted genetic modifications (Wang & Doudna, 2023).

Compared with earlier genome-editing tools, CRISPR-based systems provide simplicity in design, scalability, and the ability to modify multiple loci simultaneously, making them particularly attractive for applications in complex animal genomes (In *et al.*, 2020; Khunnonkwao *et al.*, 2024) and has become the most widely employed genome-editing tool owing to its advantages of simplicity in design, cost-effectiveness, high efficiency, and excellent repeatability when compared to ZFNs and TALENs (Komor *et al.*, 2017).

Farm animals play a vital role in societies worldwide, providing essential products such as meat, eggs, and milk, which are crucial for human nutrition, offering a rich source of energy and high-quality protein (Gao *et al.*, 2023). However the emergence of diseases is influenced not only by livestock production and feeding environments but also by genetic factors. As a result, many researchers are focused on enhancing animal genomes to improve their resistance to diseases. Gene editing technology, a precise molecular breeding approach, provides innovative solutions for accelerating genetic improvements in livestock production. This includes boosting production performance, increasing disease resistance, reducing the transmission of zoonotic diseases, and enhancing animal welfare (Perisse *et*

al., 2021). Scientists have used CRISPR to edit genes in livestock to increase disease resistance, improve growth rates, and enhance meat or milk quality. CRISPR remains a cornerstone of modern biotechnology, continuing to shape the future of genetic research and its applications across diverse animal fields (Knott *et al.* 2018; Li *et al.* 2022). Therefore the main objective of this review is to highlight the application of CRISPR-cas9 technology in animal production improvement.

2. Applications in Livestock and Animal Production

CRISPR–Cas9 technology has been widely investigated as a tool for improving livestock productivity, health, and resilience. One of the most prominent application areas is the enhancement of disease resistance through targeted modification of host susceptibility genes or immune-related 141 pathways. Such interventions have demonstrated strong potential to reduce disease prevalence, decrease mortality rates, and limit dependence on antibiotics, thereby contributing to more sustainable and environmentally responsible production systems (Sokra, 2026). Beyond disease control, CRISPR-based editing has been applied to traits associated with growth performance, feed efficiency, and product quality. Modifications affecting muscle development, fat deposition, and metabolic regulation offer opportunities to improve meat yield and nutritional value while optimizing resource use. Importantly, these genetic improvements can be achieved more rapidly and precisely than through conventional selective breeding, which is often constrained by long generation intervals and linkage drag (Wang & Doudna, 2023). Climate change presents an additional challenge to animal agriculture, necessitating the development of livestock that can tolerate heat stress and variable environmental conditions. Gene edits targeting pathways involved in thermoregulation, oxidative stress, and energy metabolism have been proposed as strategies to enhance animal resilience under increasing temperature extremes. Together, these applications position CRISPR–

Cas9 as a key enabling technology for the future of climate adaptive and sustainable livestock production (Thornton et al., 2021).

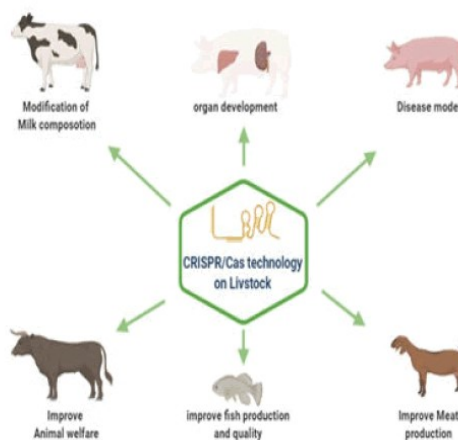
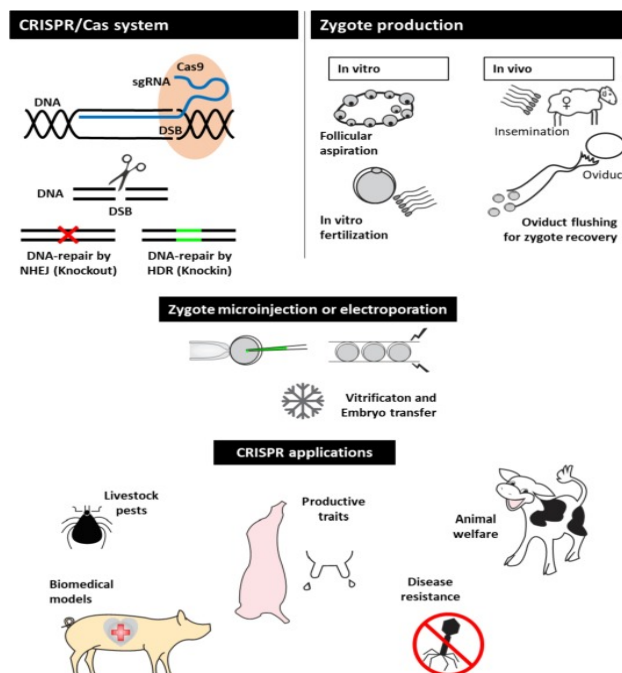


Figure 2: CRISPR/Cas mediated genome editing in major livestock species, enabling improvement of the genetics underlying traits associated with welfare, production, disease resistance and xenotransplantation.

2.1 Disease resistance

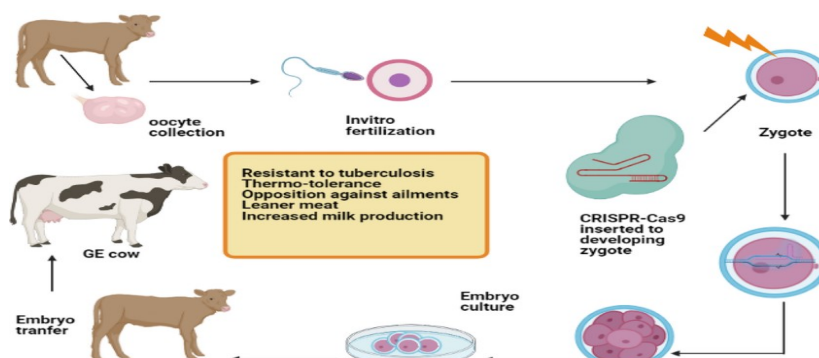
The CRISPR-Cas9 technology has been adopted in farm animals to develop disease resistance for important diseases of livestock which hinders production.

2.1.1 Mastitis resistance in cows

Mastitis, a bacterial infection of the mammary glands, poses significant economic challenges for the dairy industry. The CRISPR-Cas9 technology is being explored to enhance mastitis resistance in cows, potentially decreasing reliance on antibiotics and enhancing animal welfare (Paramasivam et al., 2023). One example involves inserting the human lysozyme gene into the β -casein locus of cows. Lysozymes are enzymes that break down bacterial cell walls. These genetically modified cows could prevent bacterial growth and resist mastitis infection by expressing lysozyme in their milk (Liu et al., 2014).

2.1.2 Tuberculosis resistance in cattle

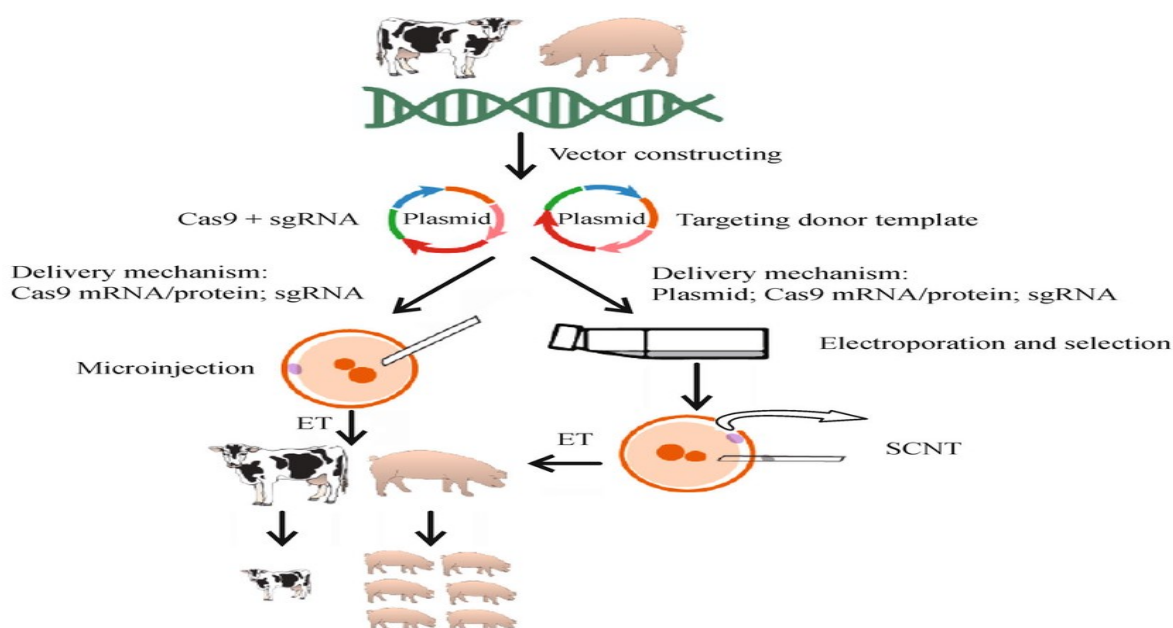
Mycobacterium bovis is a bacterium which causes bovine tuberculosis, and it is a serious concern for cattle farming. Traditional methods of breeding for disease resistance development take a long time and may affect other factors. Research using CRISPR-Cas9 has shown promise in developing tuberculosis-resistant cattle (Borham et al., 2022). Researchers used a single Cas9n to insert the NRAMP1 gene in the bovine genome (Gao et al., 2023). NRAMP1 gene has an important role in the immune response against pathogens within the cell like *Mycobacterium tuberculosis*. The use of Cas9n (generates single-strand breaks in DNA), instead of the standard Cas9 nuclease (generates double-strand breaks), enhanced safety and reduced off-target effects with precise genetic modification (Liu et al., 2014).



2.1.3 Reproductive health enhancement

CRISPR-Cas9 technology can improve reproductive health in farm animals. Research is focused on producing offspring of a desired sex in livestock. Traditional methods for sex determination, such as identifying male-specific antigens or using fluorescence in situ

hybridization, are often prone to errors, labour-intensive, and potentially harmful to embryos. It is observed that effective use of CRISPR-Cas9 to generate transgenic embryos with a labeled Y chromosome, is offering a potentially more efficient and reliable approach to sex control (Xie et al., 2020).



2.1.4 Productivity enhancement

Genome editing techniques can target genes associated with meat yield, wool production, and reproductive success. particularly *enhanced muscle mass in sheep by removing the myostatin gene*. Myostatin gene produces a protein that inhibits muscle development. By switching off this gene, animals can produce more muscle tissue, leading to increased meat production. This

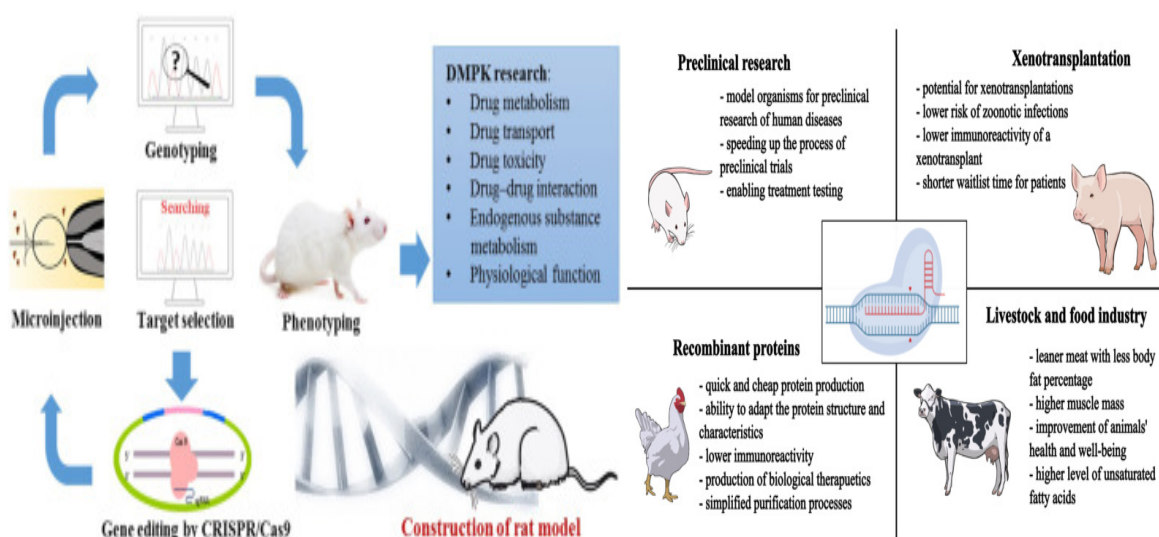
trait of increased muscle mass can also occur naturally by spontaneous mutations in the myostatin gene, as seen in the Belgian Blue breed of cattle. However, introducing these mutations through conventional breeding methods is time-consuming. Scientists have effectively used CRISPR-Cas9 to remove the myostatin gene in sheep, increasing the muscle mass. This method is significantly faster than traditional breeding and could significantly lead to the growth of sheep

breeds with increased meat production in a shorter time frame (Bhat, et al., 2017).

2.1.5 Biomedical and Experimental Animal Models

In biomedical and experimental research, CRISPR–Cas9 has revolutionized the generation of genetically defined animal models. The ability to rapidly and precisely modify specific genes has accelerated functional genomics studies, enabling direct investigation of gene function, regulatory networks, and disease mechanisms. Compared with traditional transgenic approaches, CRISPR-based methods significantly reduce time, cost, and technical complexity (Lika et al., 2026; Socheata et al., 2026). CRISPR technology has facilitated the creation of animal models that closely recapitulate human diseases, thereby improving

the translational relevance of preclinical studies. Precise introduction of disease-associated mutations allows researchers to evaluate pathophysiological processes and therapeutic interventions with greater accuracy. Furthermore, multiplex genome editing—simultaneous targeting of multiple genes—has enabled the study of polygenic traits and complex biological pathways, which are difficult to address using single-gene modification approaches (Barazesh et al., 2021). These advances have strengthened the role of animal models in drug development, toxicological assessment, and regenerative medicine research. As editing efficiency and precision continue to improve, CRISPR-based animal models are expected to play an increasingly central role in bridging basic research and clinical application.



3. Challenges and Ethical Considerations of the technology

Despite rapid technological progress, several challenges continue to limit the widespread application of CRISPR–Cas9 in animal systems. Technical concerns include off-target effects, mosaicism, variable editing efficiency, and incomplete understanding of long-term phenotypic consequences (Olabi et al., 2023). Ensuring reproducibility and genetic stability

across generations remains a critical requirement, particularly for applications involving germline modification. Ethical considerations are equally significant. Issues related to animal welfare, the moral boundaries of genetic intervention, and potential ecological risks associated with unintended gene flow have generated substantial public debate. Ethical frameworks increasingly emphasize the need to balance technological innovation with responsible stewardship of animal life and ecosystems (Somaly & Sokra, 2026).

Regulatory landscapes governing CRISPR-edited animals remain fragmented across regions. Differences in how gene-edited organisms are classified and regulated influence research priorities, commercialization pathways, and international trade. Regulatory uncertainty can discourage investment and slow technology transfer from research to application (Sokra et al., 2026).

4. Future Perspectives

Future progress in animal genome editing is expected to focus on improving delivery systems, enhancing editing precision, and minimizing unintended genomic alterations. Advances in non-viral delivery methods, embryo manipulation techniques, and tissue-specific editing strategies are likely to expand the feasibility of CRISPR applications across a wider range of animal species. Integration of CRISPR technologies with genomic selection, systems biology, and artificial intelligence-based breeding strategies represents a promising direction for maximizing genetic gains while maintaining animal welfare and genetic diversity (Chuang et al., 2021). Such integrative approaches can enable more predictive and targeted interventions, accelerating the development of resilient and high performing animal populations. Equally important is the role of responsible innovation. Transparent regulatory frameworks, stakeholder engagement, and public communication will be critical for building trust and ensuring societal acceptance of gene-edited animals. Long-term success will depend not only on technical excellence but also on ethical integrity and policy coherence (Sokra et al., 2026).

5. Conclusion and Recommendations

CRISPR–Cas9 and its advanced derivatives have fundamentally reshaped animal science by enabling precise, efficient, and versatile genome modification across research, biomedical, and production systems. The technology has accelerated genetic improvement in livestock,

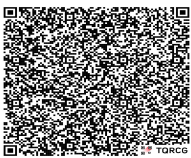
enhanced the development of sophisticated animal models, and opened new avenues for sustainable and climate resilient animal agriculture. While technical, ethical, and regulatory challenges remain, ongoing innovation and evidence-based governance provide a strong foundation for responsible application. With continued refinement and societal engagement, CRISPR technologies are poised to become indispensable tools for advancing animal health, productivity, and scientific knowledge. However, despite the potential advantages of CRISPR-Cas9, public acceptance of genetically modified agricultural products remains uncertain. Therefore Continued advancements in this technology and its underlying mechanisms promise to improve poultry products and genetically modified livestock. Overall, CRISPR-Cas9 technology offers a promising pathway for advancing livestock breeding practices, with opportunities for genetic improvement, enhanced disease resistance, and greater productivity.

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How to cite this article:

Gizachew Fentahun and Haymanot Aragaw. (2026). Application of CRISPR-Cas9 technology in animal production improvement and product industry. *Int. J. Curr. Res. Chem. Pharm. Sci.* 13(9): 8-15.
DOI: <http://dx.doi.org/10.22192/ijercps.2026.13.09.002>