

Gene-Edited Livestock for Enhanced Feed Efficiency and Metabolic Adaptation Through Precision Genomic Interventions

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Abstract

Advances in gene editing technologies have transformed the landscape of livestock production by enabling precise manipulation of genetic material associated with productivity, health, and environmental adaptability. Tools, such as CRISPR Cas9 and emerging next generation editors, allow targeted modifications that improve feed efficiency, growth performance, nutrient utilization, and stress tolerance in farm animals. This review highlights the genetic basis of feed efficiency and metabolic regulation, focusing on key genes and pathways involved in digestion, energy balance, protein synthesis, and lipid metabolism. It further explores how gene editing can be applied to improve economically important traits such as feed conversion ratio, residual feed intake, body composition, and nutrient digestibility. Integration of genetic technologies with nutritional strategies, including precision feeding and nutrigenomics, enables optimized expression of desirable traits and improved production efficiency. Species specific applications in cattle, poultry, and swine demonstrate the versatility of gene editing in addressing diverse production challenges. In addition, gene-based improvements contribute significantly to climate resilience by enhancing heat tolerance, metabolic flexibility, and stress adaptation. Despite its potential, the application of gene editing in livestock faces challenges including off target effects, ethical concerns, regulatory variability, and risks to genetic diversity. Public perception and animal welfare considerations also play critical roles in shaping adoption pathways. Future directions emphasize integration of multi omics technologies and artificial intelligence to enhance predictive breeding and precision nutrition systems. Overall, gene editing, when responsibly applied, offers a powerful approach to developing sustainable, efficient, and climate resilient livestock production systems that support global food security under changing environmental conditions.

Keywords: Feed efficiency, gene editing, genomic interventions, livestock, metabolic adaptation, precision breeding, trait improvement

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INTRODUCTION

Livestock production plays a central role in global food security by supplying high quality protein, milk, and meat to a growing population. However, increasing demand for animal products is placing pressure on feed resources, environmental sustainability, and production efficiency. Traditional breeding methods have contributed significantly to genetic improvement, yet they are often limited by long generation intervals and low precision in trait selection. In this context, gene editing technologies have emerged as powerful tools for accelerating genetic gain and improving economically important traits in livestock [1–4]. Techniques, such as CRISPR Cas9, allow precise

modification of DNA sequences, enabling targeted improvements in growth, metabolism, disease resistance, and environmental adaptation. These advances offer new opportunities to enhance productivity while reducing resource use and environmental impact [5–8].

Feed efficiency and metabolic regulation are among the most important traits influencing livestock performance and profitability [9–11]. Traits, such as feed conversion ratio, residual feed intake, growth rate, and body composition, are controlled by complex genetic networks involving energy metabolism, nutrient absorption, and hormonal regulation. In addition, gene diet interactions and epigenetic mechanisms further influence how animals respond to different nutritional environments [12–14]. Integrating molecular genetics with nutritional science has, therefore, become a promising strategy for improving production efficiency. Furthermore, gene editing provides the possibility of enhancing digestive enzyme activity, optimizing metabolic pathways, and improving stress tolerance, particularly under heat and nutritional stress conditions that are increasingly common due to climate change.

Despite significant progress, several gaps remain in the application of gene editing in livestock systems. Limited understanding of long-term genetic stability, off target effects, and interactions between edited genes and complex environmental factors restricts widespread adoption [15, 16]. In addition, species specific responses and insufficient field level validation hinder practical implementation in diverse production systems. Ethical concerns, regulatory differences across countries, and limited integration with precision nutrition strategies also constrain progress. The novelty of current research lies in combining gene editing with omics technologies and artificial intelligence to develop predictive, climate adaptive livestock systems. This integrated approach aims to bridge existing gaps by linking genotype, nutrition, and environment to achieve sustainable and efficient animal production under changing global conditions.

FUNDAMENTALS OF GENE EDITING TECHNOLOGIES

Principles of CRISPR Cas9 and Other Editing Tools

CRISPR Cas9 is a genome editing system derived from bacterial adaptive immunity. It uses a guide RNA to direct the Cas9 nuclease to a complementary DNA sequence where it creates a double strand break [5, 6, 17]. The cell then repairs the breakthrough non homologous end joining or homology directed repair enabling targeted gene disruption or insertion. Other systems, such as Cas12 and base editors, expand targeting range and allow precise nucleotide level modifications for functional genomics and breeding applications research use [2–4].

Gene Editing and Traditional Genetic Modification

Gene editing differs from traditional genetic modification in that it enables targeted changes at specific genomic loci without necessarily introducing foreign DNA. Traditional genetic modification often relies on transgenic approaches where genes from unrelated species are inserted randomly into the genome. Gene editing technologies, such as CRISPR, allow precise deletion, insertion, or substitution of nucleotides at predefined sites. This results in faster development, reduced off target effects, and more predictable trait expression compared to conventional transgenic methods in organism's systems [7, 18, 19].

Precision, Efficiency, and Heritability of Edited Traits

Precision in gene editing refers to the ability to modify specific DNA sequences with minimal unintended changes elsewhere in the genome. Efficiency describes the proportion of cells successfully edited within a given population and is influenced by delivery systems and repair pathways. Heritability indicates whether the edited trait is transmitted to subsequent generations through germline modification. High precision and efficiency improve reproducibility in research and breeding, while stable heritability ensures long term persistence of desirable genetic traits in populations framework [9, 20–22].

GENETIC BASIS OF FEED EFFICIENCY AND METABOLISM

Key Genes Regulating Feed Intake, Digestion, and Energy Balance

Key genes regulating feed intake, digestion, and energy balance include leptin, ghrelin, insulin-like growth factors, and neuropeptide Y systems. These genes influence appetite signaling, satiety, nutrient absorption, and metabolic rate. Variations in these loci affect how efficiently animals convert feed into body mass [23–26]. In livestock, polymorphisms in digestive enzyme genes and transporter proteins also shape nutrient utilization. Coordinated gene expression across hypothalamic and gastrointestinal tissues ensures balanced energy homeostasis and optimal growth performance under diverse nutritional environments conditions framework [25, 27, 28].

Pathways Involved in Protein Synthesis and Lipid Metabolism

Pathways involved in protein synthesis and lipid metabolism include mTOR signaling, AMPK regulation, insulin signaling, and PPAR mediated transcriptional networks. These pathways coordinate cellular energy status with nutrient availability, controlling muscle accretion and fat deposition. Protein synthesis depends on ribosomal activity, amino acid sensing, and translational control mechanisms. Lipid metabolism involves fatty acid oxidation, lipogenesis, and cholesterol transport. Cross talk between these pathways ensures metabolic flexibility, allowing organisms to adapt efficiently to changing dietary inputs and environmental stress conditions framework [6, 26, 29].

Role of Gene Diet Interactions in Metabolic Performance

Gene diet interactions describe the complex relationship between genetic variation and nutrient intake in shaping metabolic performance. Different genotypes respond uniquely to dietary protein, carbohydrate, and lipid levels, influencing growth efficiency and energy utilization. Nutrients can regulate gene expression through epigenetic modifications and transcriptional control mechanisms. These interactions affect enzyme activity, hormonal balance, and gut microbiome composition. Understanding gene diet interplay enables precision feeding strategies that improve productivity, health, and resilience in livestock under varying environmental and management conditions framework [27, 30, 31].

TARGET TRAITS FOR GENE EDITING

Feed Conversion Ratio and Residual Feed Intake

Feed conversion ratio and residual feed intake are primary indicators of feed efficiency in livestock. Feed conversion ratio measures the amount of feed required to produce a unit of body weight gain, while residual feed intake estimates the difference between observed and expected feed intake based on maintenance and growth. Genetic improvement of these traits reduces production costs and environmental impact in systems globally applied. Genes affecting appetite regulation, digestion, and metabolic rate contribute significantly to variation in both parameters in populations [3, 4, 9, 21].

Growth Rate and Body Composition

Growth rate and body composition are economically important traits targeted in gene editing programs for livestock improvement globally applied. Growth rate reflects the speed of weight gain over time, while body composition describes the proportion of muscle, fat, and bone in an animal. Genetic selection and editing of growth-related genes, such as myostatin and growth hormone pathways, can enhance productivity efficiency. These modifications also influence nutrient partitioning between lean tissue and adipose tissue improving carcass quality and market value [24, 29, 32, 33].

Nutrient Digestibility and Absorption

Nutrient digestibility and absorption determine how efficiently animals extract energy and nutrients from feed which is critical for sustainable and efficient animal production systems in agriculture. Genetic variation in digestive enzymes, intestinal transporters, and gut morphology influences these processes significantly. Genes regulating cellulase activity, amino acid transport, and lipid uptake are particularly important in ruminants and monogastrics. Enhancing digestibility improves feed utilization, reduces waste output, and increases overall production efficiency in livestock systems under diverse feeding conditions globally and climate variation impacts across production systems [34–37].

Stress Tolerance and Metabolic Flexibility

Stress tolerance and metabolic flexibility are essential traits enabling animals to adapt to environmental and physiological challenges. Genetic factors influencing heat stress resistance, oxidative balance, and hormonal regulation determine survival and productivity under harsh conditions. Pathways involving heat shock proteins, antioxidant systems, and energy metabolism play a central role in maintaining homeostasis. Gene based improvements in these traits support resilience, productivity, and long-term sustainability in livestock production systems globally under climate variability and nutritional stress conditions across production systems [11, 12, 31, 38].

APPLICATIONS OF GENE EDITING IN LIVESTOCK

Editing for Improved Digestive Enzyme Activity

Gene editing can enhance digestive enzyme activity by modifying genes responsible for proteases, lipases, and carbohydrases. In ruminants and monogastric species, improved enzyme expression increases breakdown of feed components and nutrient availability. Targeted changes in intestinal and pancreatic enzyme regulation improve feed efficiency and reduce undigested residues. This approach supports better utilization of low-quality feed resources and reduces feeding costs. Enhanced enzymatic efficiency also contributes to improved growth performance and reduced environmental nutrient losses in production systems widely applied globally [2–4, 6].

Modifying Metabolic Pathways for Efficient Nutrient Utilization

Gene editing allows modification of metabolic pathways involved in carbohydrate, protein, and lipid utilization. Key targets include insulin signaling, mTOR regulation, and fatty acid oxidation pathways. Adjusting these pathways improves nutrient partitioning toward muscle growth rather than fat deposition. In livestock systems, this leads to improved productivity and reduced feed input requirements. Such modifications enhance metabolic efficiency under varying dietary conditions and support sustainable production [7, 9, 19, 20, 39]. These advances contribute to optimized energy use and better overall performance in diverse farming environments globally.

Enhancing Tolerance to Heat and Nutritional Stress

Gene editing can improve tolerance to heat stress and nutritional stress by targeting genes involved in thermoregulation, oxidative stress response, and cellular protection. Heat shock proteins and antioxidant enzymes play central roles in maintaining cellular stability under adverse conditions. Improved stress tolerance helps maintain feed intake, fertility, and productivity during environmental challenges. These genetic improvements are especially valuable in tropical and subtropical production systems where heat stress is common, supporting resilience and stability in livestock production systems under climate variability conditions [7, 9, 19, 20, 39].

Species Specific Applications in Cattle, Poultry, and Swine

Species specific gene editing applications target traits relevant to cattle, poultry, and swine production systems. In cattle, edits focus on milk yield, heat tolerance, and feed efficiency traits in cattle. In poultry, modifications improve growth rate, disease resistance, and feed conversion efficiency in poultry. In swine, gene editing targets lean meat production, nutrient utilization, and stress resistance in swine. These tailored interventions improve productivity, adaptability, and resource efficiency across species, supporting sustainable livestock systems under diverse environmental and management conditions globally applied in agriculture systems [10, 24, 33–35, 40, 41].

INTEGRATION WITH NUTRITIONAL STRATEGIES

Precision Feeding for Gene Edited Animals

Precision feeding for gene edited animals involves matching nutrient supply with the specific genetic potential and metabolic needs of individual livestock. By using data from genomic selection and performance monitoring, diets can be adjusted to optimize growth, reproduction, and health outcomes. This approach reduces nutrient wastage and improves feed efficiency. Integration of sensors, modeling

tools, and feeding systems enables real time adjustments. Such strategies maximize the benefits of gene edited traits while supporting sustainable production systems in modern livestock agriculture [26, 31, 35].

Nutrigenomics and Diet-Based Gene Expression Modulation

Nutrigenomics and diet-based gene expression modulation explore how nutrients influence gene activity and metabolic pathways. Specific dietary components can upregulate or downregulate genes involved in growth, immunity, and metabolism through epigenetic and transcriptional mechanisms. This allows formulation of diets that enhance desirable traits in genetically characterized animals. Understanding nutrient gene interactions improves efficiency of production systems and animal health. It bridges molecular biology and nutrition science to design targeted feeding strategies that optimize performance and resilience in livestock systems [12, 42, 43].

Synergy Between Diet Formulation and Genetic Potential

Synergy between diet formulation and genetic potential ensures that nutrient supply aligns with the inherent biological capacity of animals. Matching feed composition with genetic traits enhances growth efficiency, reproductive performance, and health outcomes. This integration enables better utilization of nutrients and reduces production inefficiencies. Advanced modeling and genomic tools support customized diet planning based on genetic profiles. Such synergy improves sustainability, productivity, and profitability in livestock systems by maximizing the expression of desirable genetic traits under varying environmental conditions globally [26, 44, 45].

IMPACTS ON PRODUCTIVITY AND SUSTAINABILITY

Improved Feed Efficiency and Reduced Production Cost

Gene editing and advanced nutrition strategies significantly improve feed efficiency by enhancing nutrient utilization and reducing maintenance energy losses. Animals convert feed into body mass or milk more effectively, lowering the amount of feed required per unit of product. This directly reduces production cost, which is a major constraint in livestock systems. Improved efficiency also stabilizes profitability under fluctuating feed prices. Combined genetic and nutritional improvements support economically viable livestock production while maintaining consistent output quality across diverse farming conditions [6, 11, 19].

Lower Environmental Footprint Through Reduced Waste

Improved genetic traits and optimized feeding systems reduce environmental impact by lowering feed waste and nutrient excretion. Better digestion and metabolic efficiency decrease nitrogen and phosphorus losses into soil and water systems. Reduced methane production in ruminants further decreases greenhouse gas emissions. These improvements contribute to more sustainable livestock production systems by minimizing pollution and resource depletion. Enhanced efficiency ensures that fewer natural resources are required per unit of animal product, supporting environmentally responsible agriculture under increasing global demand pressures [10, 12, 37].

Contribution to Climate Resilient Livestock Systems

Gene editing and integrated nutrition contribute to climate resilient livestock systems by improving adaptability to heat stress, feed scarcity, and disease pressure. Animals with enhanced metabolic flexibility and stress tolerance maintain productivity under variable environmental conditions. These innovations help stabilize food production in regions affected by climate change. Improved resilience reduces production losses and supports food security. Combined genetic and nutritional strategies enable livestock systems to remain productive, efficient, and sustainable despite increasing environmental challenges and climate variability worldwide in agriculture systems [13, 25, 44].

ETHICAL, REGULATORY, AND SOCIAL CONSIDERATIONS

Safety Assessment and Regulatory Frameworks

Safety assessment and regulatory frameworks for gene edited livestock focus on evaluating genetic stability, off target effects, food safety, and environmental impact before approval. Regulatory agencies

require stepwise validation from laboratory studies to field trials. Risk assessment includes molecular characterization and long-term monitoring of animal health and product safety. Different countries apply varying policies, ranging from strict oversight to more flexible guidelines. Harmonized global standards are needed to ensure safe adoption while supporting innovation in animal biotechnology and livestock production systems [7, 24, 26].

Public Perception and Acceptance of Gene Edited Livestock

Public perception and acceptance of gene edited livestock depend on awareness, cultural values, ethical concerns, and trust in scientific institutions. Many consumers differentiate between gene editing and traditional genetic modification, influencing acceptance levels. Transparent communication about safety, benefits, and limitations is essential to build confidence. Misunderstanding of technology can lead to resistance despite scientific evidence. Engagement with stakeholders, including farmers, consumers, and policymakers, helps improve acceptance and supports responsible adoption of gene editing in food production systems globally applied [27, 46, 47].

Animal Welfare Considerations

Animal welfare considerations in gene edited livestock focus on ensuring that genetic modifications do not cause pain, suffering, or reduced quality of life. Edited traits must be evaluated for effects on health, behavior, reproduction, and long-term physiological stability. Welfare assessment includes monitoring growth patterns, disease resistance, and adaptability to environmental stress. Ethical frameworks emphasize minimizing harm while improving productivity. Responsible use of gene editing should align with welfare standards and promote healthier animals within sustainable livestock production systems globally applied [23, 28, 41].

CHALLENGES AND LIMITATIONS

Off Target Effects and Unintended Consequences

Off target effects refer to unintended modifications in genomic regions other than the intended target site during gene editing. These changes may disrupt normal gene function, leading to unpredictable physiological or developmental consequences. Even small sequence errors can influence metabolism, growth, or disease susceptibility. Detecting and minimizing these effects requires advanced screening methods and high-fidelity editing systems. Ensuring accuracy remains a key challenge, as unintended consequences can compromise safety, performance, and reliability of gene edited livestock applications in production systems [2, 6, 31].

Genetic Diversity and Long-Term Stability

Genetic diversity and long-term stability are important considerations in gene edited populations. Overreliance on specific edited traits may reduce overall genetic variation, increasing vulnerability to diseases and environmental changes. Maintaining a broad genetic base is essential for sustainable breeding programs. Additionally, long term stability of edited traits across generations must be confirmed through germline transmission studies. Epigenetic changes and gene interactions may alter trait expression over time, requiring continuous monitoring to ensure consistent performance and adaptability in livestock populations [8, 19, 26, 35].

Technical and Economic Constraints

Technical and economic constraints limit widespread adoption of gene editing in livestock systems. Advanced tools require specialized laboratories, skilled personnel, and high-cost infrastructure. Delivery of gene editing components into embryos or cells remains technically challenging in many species. Regulatory compliance and validation further increase costs and time requirements. Small scale producers may face barriers to access these technologies. Economic feasibility depends on balancing research investment with long term productivity gains and market acceptance in livestock production systems globally applied agriculture contexts [11, 12, 40, 46, 48, 49].

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Advanced Editing Tools Beyond CRISPR Cas9

Future gene editing is expanding beyond CRISPR Cas9 to include base editing, prime editing, and epigenome editing technologies. These systems enable more precise nucleotide changes without creating double strand breaks, reducing unintended mutations. Prime editing allows targeted insertions, deletions, and substitutions with higher accuracy. Ongoing research focuses on improving delivery systems and expanding species applicability. These advancements aim to increase safety, precision, and efficiency in livestock genetic improvement while minimizing biological risks associated with earlier genome editing approaches in agriculture systems.

Integration with Omics Technologies and Artificial Intelligence

Integration of genomics, transcriptomics, proteomics, and metabolomics with artificial intelligence is transforming livestock research. Omics technologies provide large scale biological data that reveal gene function, metabolic pathways, and trait associations. Artificial intelligence enables pattern recognition, predictive modeling, and decision support for breeding and nutrition strategies. Together, these tools enhance understanding of complex gene environment interactions. This integration supports precision livestock systems by improving selection accuracy, optimizing feeding strategies, and accelerating development of high performing and resilient animal populations in agriculture systems.

Development of Region Specific and Climate Adaptive Livestock

Future livestock development focuses on creating region specific and climate adaptive breeds tailored to local environmental conditions. Gene editing combined with selective breeding can enhance heat tolerance, disease resistance, and feed efficiency in specific ecological zones. This approach is especially important for tropical and arid regions facing climate variability. Animals adapted to local feed resources and environmental stress improve productivity and sustainability. Such strategies support food security, reduce production risks, and strengthen resilience of livestock systems under changing global climate conditions.

Policy and Innovation Pathways for Adoption

Effective policy and innovation pathways are essential for responsible adoption of gene editing in livestock systems. Clear regulatory frameworks must balance innovation with safety, ethical standards, and public trust. Investment in research infrastructure, capacity building, and international collaboration supports technological advancement. Policies should encourage transparent risk assessment and equitable access for farmers. Public engagement and stakeholder participation improve acceptance and informed decision making. Coordinated efforts between governments, research institutions, and industry are critical for sustainable integration of gene editing technologies globally.

CONCLUSION

Gene editing technologies represent a major advancement in livestock improvement by enabling precise modification of genes associated with productivity, metabolism, and environmental adaptation. When combined with modern nutritional strategies, these tools provide new opportunities to enhance feed efficiency, growth performance, and resilience to climatic and nutritional stress. Applications across cattle, poultry, and swine demonstrate strong potential for improving both economic efficiency and sustainability in animal production systems. Despite these benefits, challenges, such as off target effects, regulatory complexity, ethical concerns, and potential impacts on genetic diversity, must be carefully managed. Long term success depends on rigorous safety evaluation, responsible innovation, and transparent communication with society. Future progress will likely be driven by integration of gene editing with omics technologies and artificial intelligence, enabling more precise and predictive livestock management. Overall, gene-based innovation offers a promising pathway toward sustainable, climate resilient, and efficient animal agriculture.

REFERENCES

1. Huang L, Zhou M, Abbas G, Li C, Cui M, Zhang XE, et al. A cancer cell membrane-derived biomimetic nanocarrier for synergistic photothermal/gene therapy by efficient delivery of

-
- CRISPR/Cas9 and gold nanorods. *Adv Healthc Mater.* 2022;11:2201038. doi: 10.1002/adhm.202201038.
2. Lu Z, Zhang L, Mu Q, Liu J, Chen Y, Wang H, et al. Progress in research and prospects for application of precision gene-editing technology based on CRISPR-Cas9 in the genetic improvement of sheep and goats. *Agriculture.* 2024;14:487. doi: 10.3390/agriculture14030487.
 3. Popova J, Bets V, Kozhevnikova E. Perspectives in genome-editing techniques for livestock. *Animals (Basel).* 2023;13(16):2580. doi: 10.3390/ani13162580.
 4. Raza SHA, Hassanin AA, Pant SD, Bing S, Sitohy MZ, Abdelnour SA, et al. Potentials, prospects and applications of genome editing technologies in livestock production. *Saudi J Biol Sci.* 2022;29(4):1928–35. doi: 10.1016/j.sjbs.2021.11.037.
 5. Wang Y, Cui X, Chen Z. Innovations in cattle breeding technology: Prospects in the era of gene editing. *Animals (Basel).* 2025;15(10):1364. doi: 10.3390/ani15101364.
 6. Sokra I, Somaly S, Socheata C, Meta H. CRISPR-Cas9-based genome editing in microbial biotechnology: Advances in metabolic engineering, fermentation systems, and industrial applications. In: Ito M, Narumi I, Doukyu N, editors. *Extremophiles for a Sustainable Future.* Singapore: Springer Nature; 2026. p. 379–387. doi: 10.1007/978-981-95-6970-0_20.
 7. Gutási A, Hammer SE, El-Matbouli M, Saleh M. Review: Recent applications of gene editing in fish species and aquatic medicine. *Animals (Basel).* 2023;13(7):1250. doi: 10.3390/ani13071250.
 8. Wang P, Zhang L, Xie Y, Wang N, Tang R, Zheng W, et al. Genome editing for cancer therapy: Delivery of Cas9 protein/sgRNA plasmid via a gold nanocluster/lipid core-shell nanocarrier. *Adv Sci (Weinh).* 2017;4(11):1700175.
 9. Karavolias NG, Horner W, Abugu MN, Evanega SN. Application of gene editing for climate change in agriculture. *Front Sustain Food Syst.* 2021;5:685801.
 10. Camargo LS, Saraiva NZ, Oliveira CS, Carmickle A, Lemos DR, Siqueira LG, et al. Perspectives of gene editing for cattle farming in tropical and subtropical regions. *Anim Reprod.* 2022;19:e20220108.
 11. Hoque M, Mondal S. Transgenic animals: Prospects for improving livestock productivity. In: *Genetic and Reproductive Approaches for Sustainable Livestock Production.* Academic Press; 2026. p. 239–258.
 12. Gutierrez-Reinoso MA, Aponte PM, Garcia-Herreros M. Genomic analysis, progress and future perspectives in dairy cattle selection: A review. *Animals (Basel).* 2021;11(3):599.
 13. Parsad R, Ahlawat S, Bagiyal M, Arora R, Gera R, Chhabra P, et al. Climate resilience in goats: A comprehensive review of the genetic basis for adaptation to varied climatic conditions. *Mamm Genome.* 2025;36(1):151–61.
 14. Andersen LK, Thompson NF, Abernathy JW, Ahmed RO, Ali A, Al-Tobasei R, et al. Advancing genetic improvement in the omics era: Status and priorities for United States aquaculture. *BMC Genomics.* 2025;26(1):155.
 15. Sharma P, Doultani S, Hadiya K, George L, Highland H. Overview of marker-assisted selection in animal breeding. *HISTORY.* 2024;9(11).
 16. Andersen LK, Thompson NF, Abernathy JW, Ahmed RO, Ali A, Al-Tobasei R, et al. Advancing genetic improvement in the omics era: Status and priorities for United States aquaculture. *BMC Genomics.* 2025;26(1):155.
 17. Gatica-Arias A. The regulatory current status of plant breeding technologies in some Latin American and the Caribbean countries. *Plant Cell Tissue Organ Cult.* 2020;141(2):229–42.
 18. von Keyserlingk MA, Mills KE, Weary DM. Attitudes of western Canadian dairy farmers toward technology. *J Dairy Sci.* 2024;107(2):933–43.
 19. Wang J, Zhang L, Pan C, Lan X, Xing B, Li M. Application of gene editing technology in livestock: Progress, challenges, and future perspectives. *Agriculture.* 2025;15(20):2155.
 20. Islam MA, Rony SA, Rahman MB, Cinar MU, Villena J, Uddin MJ, et al. Improvement of disease resistance in livestock: Application of immunogenomics and CRISPR/Cas9 technology. *Animals (Basel).* 2020;10(12):2236.
 21. Moran MN, Jones DB, Jensen SA, Marcoli R, Jerry DR. Optimising commercial traits through gene editing in aquaculture: Strategies for accelerating genetic improvement. *Rev Aquac.* 2024;16(3):1127–59.
-

22. Van Eenennaam AL, Young AE. The use of gene editing techniques in dairy cattle breeding. In: *Advances in Breeding of Dairy Cattle*. Burleigh Dodds Science Publishing; 2019. p. 571–602. doi: 10.19103/as.2019.0058.27.
23. Wadood AA, Bordbar F, Zhang X. Integrating omics approaches in livestock biotechnology: Innovations in production and reproductive efficiency. *Front Anim Sci*. 2025;6:1551244.
24. Ngeno K. Utilization of genome editing for livestock resilience in changing environment. *Black Sea J Agric*. 2023;6(3):314–20.
25. Gao Z, Zheng J, Xu G. Molecular mechanisms and regulatory factors governing feed utilization efficiency in laying hens: Insights for sustainable poultry production and breeding optimization. *Int J Mol Sci*. 2025;26(13):6389.
26. Mishu MA, Nath SK, Sohiddullah M, Hossain MT. Advancement of animal and poultry nutrition: Harnessing the power of CRISPR-Cas genome editing technology. *J Adv Vet Anim Res*. 2024;11(2):483.
27. Wadood AA, Bordbar F, Zhang X. Integrating omics approaches in livestock biotechnology: Innovations in production and reproductive efficiency. *Front Anim Sci*. 2025;6:1551244.
28. Wadood AA, Bordbar F, Zhang X. Integrating omics approaches in livestock biotechnology: Innovations in production and reproductive efficiency. *Front Anim Sci*. 2025;6:1551244.
29. Borgohain T, Suma R, Muttappagol M, Saikia B, Keithellakpam A, Laskar A, et al. Precision breeding in a changing climate: Unlocking resilience through omics and gene editing. *Funct Integr Genomics*. 2026;26(1):26.
30. Kiran BR, Prasad MN, Mohan SV. Synthetic biology: An emerging field for developing economies. In: *Bioremediation and Bioeconomy*. Elsevier; 2024. p. 767–787.
31. Ullah Z, Iqbal J, Abbasi BA, Ijaz S, Anjum A, Yaseen T, et al. Current challenges and recent advancements in the adoption of omics to enhance biofortification. In: *Crop Biofortification: Biotechnological Approaches for Achieving Nutritional Security under Changing Climate*. 2025. p. 61–88.
32. Pozzebon M, Guldbrandtsen B, Sandøe P. Gene editing cattle for enhancing heat tolerance: A welfare review of the “PRLR-SLICK cattle” case. *Nanoethics*. 2024;18(2):6. doi: 10.1007/s11569-024-00455-8.
33. Yunes MC, Osório-Santos Z, von Keyserlingk MA, Hötzel MJ. Gene editing for improved animal welfare and production traits in cattle: Will this technology be embraced or rejected by the public? *Sustainability*. 2021;13(9):4966.
34. Yunes MC, Osório-Santos Z, von Keyserlingk MA, Hötzel MJ. Gene editing for improved animal welfare and production traits in cattle: Will this technology be embraced or rejected by the public? *Sustainability*. 2021;13(9):4966.
35. Van Eenennaam AL, Young AE. Gene editing in livestock: Promise, prospects and policy. *CABI Rev*. 2019;2018:1–4.
36. Mueller ML, Van Eenennaam AL. Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. *CABI Agric Biosci*. 2022;3(1):13.
37. Said S, Agung PP, Putra WPB, Kaiin EM. The role of biotechnology in animal production. *IOP Conf Ser Earth Environ Sci*. 2020;492(1):012035. doi: 10.1088/1755-1315/492/1/012035.
38. D’Occhio M, De Loos F. Strategies to enable the adoption of animal biotechnology to sustainably improve global food safety and security.
39. Yuan YG, Liu SZ, Farhab M, Lv MY, Zhang T, Cao SX. Genome editing: An insight into disease resistance, production efficiency, and biomedical applications in livestock. *Funct Integr Genomics*. 2024;24(3):81.
40. Zhao J, Lai L, Ji W, Zhou Q. Genome editing in large animals: Current status and future prospects. *Natl Sci Rev*. 2019;6(3):402–20.
41. Panda S, Sahu K, Sekhar R, Dash P. Molecular toxicity and its remediation in genetically engineered animals. In: *Advances and Applications in Biotechnology*. CRC Press. p. 144–166.

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42. Wolabu TW, Mahmood K, Chen F, Torres-Jerez I, Udvardi M, Tadege M, et al. Mutating alfalfa COUMARATE 3-HYDROXYLASE using multiplex CRISPR/Cas9 leads to reduced lignin deposition and improved forage quality. *Front Plant Sci.* 2024;15:1363182.
 43. Babaniyi GG, Babaniyi BR, Aransiola SA, Sawicka B, editors. *Biotechnology of Climate-Smart Agriculture in Food Security and Sustainable Farming*. CRC Press; 2025.
 44. Zenda T, Liu S, Dong A, Duan H. Advances in cereal crop genomics for resilience under climate change. *Life (Basel).* 2021;11(6):502.
 45. Khalil AM. Traditional strategies and cutting-edge technologies used for animal breeding: A comprehensive review. *Sustain Food Connect.* 2025;1(1):1–0.
 46. Shriver A, McConnachie E. Genetically modifying livestock for improved welfare: A path forward. *J Agric Environ Ethics.* 2018;31(2):161–80.
 47. Lopes MA. Repensando o melhoramento de plantas e o sistemas de sementes na era de mudanças exponenciais. *Cienc Agrotecnol.* 2023;47:e0001R23.
 48. Montoya JD, Hernandez D, Velasco J. Synthetic biology in the realm of genome engineering for improved biocatalysts and production. In: *Biofoundry Techniques for Biotechnology Applications*. 2026. p. 257–278.
 49. MacLaren C, Storkey J, Menegat A, Metcalfe H, Dehnen-Schmutz K. An ecological future for weed science to sustain crop production and the environment. A review. *Agron Sustain Dev.* 2020;40(4):24.