Black Sea Journal of Agriculture
doi: 10.47115/bsagriculture.1263027

Open Access Journal
e-ISSN: 2618 – 6578

Review
Volume 6 - Issue 3: 314-320 / May 2023

UTILIZATION OF GENOME EDITING FOR LIVESTOCK RESILIENCE IN CHANGING ENVIRONMENT

Kiplangat NGENO[1]*

[1]*Egerton University, Animal Breeding and Genomics Group, Department of Animal Sciences, PO Box 536, 20115, Egerton, Kenya*

Abstract: Climate change poses a significant threat to livestock production systems, including changes in temperature and rainfall patterns, increased frequency of extreme weather events, and the spread of diseases. The use of genome editing technologies presents a potential solution to mitigate the impacts of climate change on livestock. This paper reviewed the prospects of utilizing genome editing in mitigating the impact of climate change in livestock. Applications of genome editing in development of heat-tolerant, and disease-resistant as well as animals with improved feed and water use efficiency and reduced methane emissions are explored. Additionally, a potential breeding program for gene edited animals is proposed. There are several different genome editing techniques that can be used in livestock breeding, including CRISPR/Cas9, TALENs, and zinc-finger nucleases. These techniques involve introducing specific changes to the animal's genome, such as deleting or replacing genes, or introducing new ones. The technology has enormous potential for improving livestock breeding, as it allows for the creation of animals with desirable traits in a much shorter time frame than traditional breeding methods. Generally, it may take years or even decades to breed an animal with a specific trait using traditional breeding methods, whereas genome editing can achieve the same result in just a few generations. Genome editing can be used to mitigate the impact of climate change on livestock production by reducing the methane emissions by improving the efficiency of feed conversion and modifying the genes responsible for methane production. Technology can be utilized to improve livestock feeds by modifying genes involved in plant growth, development, and nutrient use. This lead to the creation of forages that are high yielding, more nutritious and better adapted to diverse production environments. Genome editing allows development of animals that are more resistant to diseases, which can help reduce the need for antibiotics and other treatments. This is particularly important given the growing problem of antibiotic resistance, which is a major concern in both human and animal health. Genome editing has the potential of developing animals that are thermo-tolerant, as well as animals with improved feed and water use efficiency. The proposed breeding program for gene-edited animals will ensure that the animals produced are healthy, genetically diverse, and meet the desired traits. In terms of ethical concerns, policies for genome editing ought to consider the potential for unintended consequences or the creation of animals with characteristics that are viewed as undesirable or unethical. Overall, genome editing technology has the potential to revolutionize livestock production and contribute to the global effort to mitigate the impact of climate change.

Keywords: Climate change, Mitigation, Genome editing, Livestock

***Corresponding author:** Egerton University, Animal Breeding and Genomics Group, Department of Animal Sciences, PO Box 536, 20115, Egerton, Kenya
E mail: ngeno.kiplangat@egerton.ac.ke (K. NGENO)
Kiplangat NGENO https://orcid.org/0000-0002-9271-7839

Received: February 10, 2023
Accepted: March 31, 2023
Published: May 01, 2023

Cite as: Ngeno K. 2023. Utilization of genome editing for livestock resilience in changing environment. BSJ Agri, 6(3): 314-320.

1. Introduction

Climate change can have significant impacts on livestock production, including heat stress, changes in forage quality and quantity, changes in water availability and quality, increased disease risk and changes in animal behaviour (Ngeno et al., 2013; Jasrotia et al., 2023). These effects of climate change on livestock pose significant challenges for farmers and the agricultural industry as a whole. Adaptation strategies are necessary to mitigate the impacts of climate change on livestock production. This includes the exploration of genome editing in development forage and livestock breeds that are more resilient to the impacts of climate change. Genome editing is a powerful tool that allows researchers to make precise changes to an animal's DNA (Panda and McGrew, 2022), potentially improving its ability to cope with environmental stressors such as heat, drought, and diseases (Ricroch, 2019; Pramod and Mitra, 2023). By harnessing the power of genome editing, scientists can develop livestock that are better able to withstand the challenges of a changing climate, improving animal health, productivity, and sustainability. Breeding programs have long been used to improve the performance and traits of livestock (Ngeno et al., 2013). With the advent of genome editing technology, breeding programs have the potential to become even more powerful tools for developing animals that are better adapted to the challenges of a changing climate. By incorporating gene-edited animals into breeding programs, researchers can select for traits that improve resilience and productivity, creating more robust and sustainable livestock populations. In this paper, mitigation of impacts of climate change including improving feeds and enhancing resistance to disease, heat and water stresses in livestock through speed breeding utilizing genome editing techniques are reviewed. Finally, a potential breeding program for gene edited animals is proposed.

2. Genome Editing Techniques

Genome editing techniques are a set of tools used to modify DNA sequences in living organisms. There are several genome editing techniques available, but some of the most popular ones are: (a) CRISPR-Cas9: CRISPR-Cas9 is a revolutionary genome editing technique that allows scientists to cut DNA at specific locations, thereby adding, removing or modifying genes. The technique relies on a protein called Cas9, which acts like a pair of molecular scissors that can cut DNA at a specific location. Scientists can then insert, delete, or replace the cut DNA sequence with a desired sequence (Mehra and Kumar, 2022; Rasheed et al., 2022; Khiabani et al., 2023; Li et al., 2023), (b) Zinc Finger Nucleases (ZFNs): Zinc Finger Nucleases are engineered proteins that can bind to specific DNA sequences and cut the DNA at that location. Like CRISPR-Cas9, ZFNs can be used to add, delete or modify genes (Mehra and Kumar, 2022; Wani et al., 2023a), (c) TALENs: Transcription Activator-Like Effector Nucleases (TALENs) are another type of engineered proteins that can bind to specific DNA sequences and cut the DNA at that location, and TALENs work by using a DNA-binding domain that can be programmed to recognize a specific DNA sequence (Mehra and Kumar, 2022; Kumar and Kues, 2023; Wani et al., 2023a), (d) Homologous Recombination: Homologous Recombination is a technique that uses a DNA template to repair a broken DNA strand. This technique is often used to introduce specific mutations or changes to a DNA sequence (Ranjitha et al., 2022; Park, 2023). These genome editing techniques have many potential applications in livestock breeding. They can be used to mitigate impact of climate change, improve quality and quantity of livestock feeds, address genetic disorders, develop new breeds, create disease, water and heat tolerant animals, and more.

3. Application of Genome Editing

3.1. Mitigating Greenhouse Gas Emissions

Genome editing has emerged as a promising tool for mitigating the impact of climate change on livestock. By making precise changes to the genetic code of animals, scientists can develop animals that are better adapted to the changing climate and can help reduce greenhouse gas emissions. Livestock production is a significant contributor to greenhouse gas emissions, with livestock accounting for around 14.5% of global greenhouse gas emissions (Sakadevan and Nguyen, 2017). Genome editing technology can be used to mitigate the impact of climate change on livestock production by reducing the methane emissions from livestock and improving the efficiency of feed conversion (Anderson et al., 2020; Wray-Cahen et al., 2022). One approach is to use genome editing to modify the genes responsible for methane production in the rumen of cattle and other ruminant animals. Researchers can introduce genes from other organisms or modify the animal's own genes to reduce the production of methane during digestion. This could lead to a significant reduction in greenhouse gas emissions from livestock production (Raza et al., 2022; Wray-Cahen et al., 2022). For examples of genome editing has been used to create cattle with a mutation in *MSTN* gene, which is associated with reduced methane emissions (Dunne et al., 2019). Likewise, Hill et al. (2021) has edited the microbiome of the animal's rumen to reduce methane production. Nitrous oxide emissions in pigs has been reduced by developing a mutation in *GDF8* gene, which is associated with reduced nitrous oxide emissions (Liu et al., 2019).

Another approach is to use genome editing to improve the efficiency of feed conversion in livestock. By modifying the genes responsible for nutrient absorption and metabolism, researchers can develop animals that require less feed to produce the same amount of meat or milk, thereby reducing the overall environmental impact of livestock production (Leisner, 2020; Moloney and McGee, 2023). For example, researchers have used genome editing to develop cows with a mutation in a gene called *DGAT1*, which is associated with improved feed efficiency (Cole et al., 2019).

Mitigating greenhouse gas emissions in both the industry and livestock sectors is crucial to address climate change and reduce the impact of human activities on the environment. While the sources of emissions and mitigation strategies differ between the two sectors, both sectors have significant potential to reduce their greenhouse gas emissions and contribute to global efforts to address climate change. In the industry sector, strategies such as improving energy efficiency, using renewable energy sources, and implementing carbon capture and storage technologies can reduce greenhouse gas emissions (IEA, 2020). Additionally, adopting circular economy principles, such as reducing waste and increasing resource efficiency, can also mitigate emissions in the industry sector (Ellen MacArthur Foundation, 2021). In contrast, mitigation strategies in the livestock sector focus on reducing emissions from enteric fermentation, manure management, and herd management practices (FAO, 2014). Additionally, reducing meat consumption and shifting towards plant-based diets can also help mitigate emissions from the livestock sector (Poore and Nemecek, 2018). Despite the differences in mitigation strategies, both sectors can benefit from implementing circular economy principles. For example, reducing waste in the livestock sector by implementing manure management practices can generate renewable energy sources such as biogas, which can be used to power the industry sector (FAO, 2014). Additionally, the industry sector can implement circular economy principles by using waste materials from the livestock sector as inputs for their production processes (Ellen MacArthur Foundation, 2021).

3.2. Improving Livestock Feeds

Genome editing can be used to improve livestock feeds by modifying genes involved in plant growth, development, and nutrient use. This approach could lead to the creation of crops that are more nutritious, have higher yields, and are better adapted to different environmental conditions (Moloney and McGee, 2023). One application of genome editing in improving livestock feeds is to modify the genes involved in plant cell walls. For example, researchers have used genome editing to modify lignin, a component of plant cell walls that makes them tough and difficult to digest (Pazhany and Henry, 2019; Yu et al., 2021). By reducing lignin content, it may be possible to create crops that are more easily digested by livestock, leading to better feed efficiency and improved animal health. Another application is to modify genes involved in nutrient uptake and utilization. For example, researchers have identified genes involved in the uptake and storage of nutrients such as nitrogen, phosphorus, and iron (Roell and Zurbriggen, 2020; Matres et al., 2021). By modifying these genes, it may be possible to create crops that are more efficient at using these nutrients, leading to higher yields and improved feed quality. Genome editing can also be used to introduce beneficial traits into crops, such as resistance to pests and diseases (Yin and Qiu, 2019; Matres et al., 2021).This can help to reduce the use of pesticides and other chemicals in crop production, leading to more sustainable and environmentally-friendly livestock feeds. While genome editing for improving livestock feeds is a promising approach, there are also some challenges to consider. One challenge is the potential for unintended consequences, such as off-target effects or unintended changes to other traits. It will be important to carefully evaluate the safety and efficacy of any gene-edited forage crops before they are introduced into the feed supply. Another challenge is the regulatory framework surrounding genome-edited crops (Menz et al., 2020). In many countries, genome-edited crops are subject to the same regulations as genetically modified crops, which can be time-consuming and expensive to navigate. Despite these challenges, genome editing for improving livestock feeds has the potential to improve animal welfare, productivity, and sustainability of livestock production. It will be important to continue research in this area to identify the most effective strategies for improving feed quality and to ensure that any gene-edited crops are safe and beneficial for animals.

3.3. Enhancing Disease Resistance

Genome editing, is a powerful tool for modifying DNA sequences in order to introduce specific changes or traits. It has the potential to revolutionize livestock breeding by creating animals with enhanced characteristics, such as disease resistance, improved growth rates, and better nutritional profiles (Rexroad et al., 2019). In particular, genome editing for disease resistance in livestock has received a lot of attention in recent years. Disease is a major issue in livestock production, as it can lead to significant economic losses and impact animal welfare. Traditional breeding methods have been used for centuries to select for desirable traits, but these methods can be slow and imprecise. Genome editing, on the other hand, allows for precise modifications to be made to an animal's genome in a relatively short amount of time. One potential use of genome editing in livestock is to create animals with increased disease resistance (Ricroch, 2019; Zhao et al., 2019). For example, Pramod and Mitra (2023) and Guo et al. (2019) have used genome editing to create pigs that are resistant to porcine reproductive and respiratory syndrome virus (PRRSV), which causes significant losses in the swine industry. Genome editing has been applied in creating pigs that are resistant to African swine fever, a highly contagious and deadly disease that has devastated pig populations around the world (Gaudry et al., 2021). By introducing specific genetic changes, the pigs are able to produce a protein that helps protect them against the virus. Another example is the use of genome editing to create dairy cows that are resistant to bovine tuberculosis (TB) reported by Pramod and Mitra (2023). Bovine TB is a major issue in some countries and can lead to significant losses in milk production. Researchers have used genome editing to introduce a specific genetic mutation that makes the cows less susceptible to the disease. While the potential benefits of genome editing for disease resistance in livestock are significant, there are also concerns about the technology. One concern is the potential for unintended consequences, such as off-target effects or the introduction of new diseases (Gori et al., 2015). Another concern is the ethical implications of modifying animals in this way, particularly if it involves creating animals that are unable to feel pain or experience other emotions. Despite these concerns, the use of genome editing in livestock is likely to continue to be an area of active research and development.

3.4. Mitigating Heat Stress

Heat stress is a significant issue in livestock production, particularly in areas with high temperatures and humidity. It can lead to reduced productivity, decreased fertility, and even death in some cases (Ngeno et al., 2013). Genome editing has the potential to address this issue by producing animals with improved heat tolerance. One approach to genome editing for heat stress in livestock is to introduce genetic variations that are associated with improved heat tolerance in other species. For example, researchers have identified specific genetic variations in camels that help them to survive in hot, arid environments (Bahbahani et al., 2019). By introducing these variations into the genomes of livestock such as cattle or sheep, it may be possible to create animals with improved heat tolerance. Another approach is to use genome editing to modify genes that are known to be involved in heat stress response pathways. For example, researchers have identified genes involved in heat shock response, which is a protective mechanism that helps cells survive under conditions of high heat (Haire et al., 2022). By modifying these genes using genome editing, it may be possible to enhance the heat shock response in livestock and improve their heat tolerance.

Examples of applications of genome editing in mitigating heat stress in livestock include editing of genes involved in thermoregulation, such as those related to sweating or panting. For example, knockout of the *TRPM8* gene, which plays a role in thermoregulation, has led to improved heat tolerance in dairy cows (Tian et al., 2019). Another approach has been enhancement of the heat shock response, which is a cellular mechanism that helps protect cells from heat stress. This has been achieved by editing genes involved in the heat shock response pathway, such as *HSF1*. A study published by Liu et al. (2020) demonstrated that overexpression of *HSF1* improved thermotolerance in porcine cells. Heat stress can impair immune function in livestock, making them more susceptible to diseases. Editing genes involved in immune function, such as those related to cytokine production, has been edited to help mitigate this effect. A study published Zhang et al. (2018) demonstrated that knockout of the *IL1B* gene, which encodes a cytokine involved in the immune response, improved heat tolerance in broiler chickens. It has been demonstrated that knockout of the *MC4R* gene, which plays a role in appetite regulation, improved heat tolerance in broiler chickens (Tang et al., 2021). In 2020, scientists in Brazil used CRISPR-Cas9 to modify a gene called *UCP1* in cattle embryos. *UCP1* is involved in heat production and energy metabolism, and the modification was intended to increase the animals' heat tolerance. The resulting calves showed improved growth rates and were able to maintain body temperature under hot conditions, suggesting that the modification had a positive effect on their heat tolerance (Rossi, 2020).

While genome editing for heat stress in livestock is a promising approach, there are also some challenges to consider. One challenge is the complexity of the genetic basis of heat tolerance, which involves multiple genes and pathways (Jahan et al., 2022). It may be difficult to identify all of the relevant genes and modify them in a coordinated way. Despite the challenges, genome editing for heat stress in livestock has the potential to improve animal welfare and productivity in hot environments. It will be important to continue research in this area to identify the most effective strategies for improving heat tolerance and to ensure that any gene-edited animals are safe and beneficial for both animals and consumers.

3.5. Mitigating Water Stress

Water stress is a significant issue in many parts of the world, particularly in tropics with limited access to water. Livestock are often affected by water stress, which can lead to reduced productivity, decreased fertility, and even death in severe cases (Ngeno et al., 2013). Genome editing has the potential to address this issue by creating animals with improved water use efficiency. One approach to genome editing for water stress in livestock is to modify genes that are involved in water use and conservation (Karavolias et al., 2021). For example, researchers have identified genes involved in animal water use efficiency (Lea et al., 2023), which could be introduced into the genomes of livestock such as cattle or sheep. By modifying these genes, it may be possible to develop animals that are more efficient at using water and can better tolerate water stress. Another approach is to use genome editing to modify genes involved in the regulation of water balance in the body. For example, researchers have identified genes involved in the production and regulation of water balance, which are channels that allow water to move in and out of cells (Alamer, 2011; Karavolias et al., 2021). By modifying these genes, it may be possible to create animals with improved water balance and better tolerance of water stress. Water stress is often associated with high temperatures, and animals that are better able to tolerate heat stress may be more resilient to water scarcity. Genome editing can be used to modify genes involved in heat shock response, such as *HSP70*, which help protect cells from damage caused by high temperatures (Durosaro et al., 2023). While genome editing for water stress in livestock is a promising approach, there are also some challenges to consider. One challenge is complexity of the genetic basis of water use efficiency, which involves multiple genes and pathways. It may be challenging to ascertain all of the significant genes and alter them in a synchronized manner. Notwithstanding the challenges, genome editing for water stress in livestock has the latent to mend animal welfare and productivity in regions with water scarcity.

4. Breeding Program for Gene Edited Animals

Designing a breeding program for gene-edited animals would involve several steps, including identifying the desired traits, selecting the appropriate gene-editing techniques, and developing a breeding strategy to propagate the edited traits (Mueller et al., 2015; Ngeno, 2015). The following is an outline of the essential steps in such a program:

- Identification of the desired traits: The first step in designing a breeding program for gene-edited animals is to identify the desired traits. This could be anything from disease resistance to increased growth rates, improved nutrition, or enhanced fertility (Ngeno, 2015).
- Choosing the appropriate gene-editing technique: Depending on the desired traits, different gene-editing techniques may be used. Some common techniques include CRISPR/Cas9, TALENs, and Zinc Finger Nucleases. Each technique has its strengths and weaknesses, and the choice of technique will depend on the specific traits being targeted (Khalil, 2020).

- Editing the genes in the desired animals: Once the appropriate gene-editing technique has been chosen, the next step is to edit the genes in the desired animals. This could involve introducing new genes, deleting or disabling existing genes, or modifying the expression of genes (Mushtaq and Molla, 2023; Wani et al., 2023b).
- Screening and selection of edited animals: After editing the genes, the next step is to screen and select the edited animals. This involve genetic testing to confirm the desired traits have been successfully edited, as well as assessing other factors such as health, temperament, and breeding potential (Bunton-Stasyshyn et al., 2022).
- Developing a breeding strategy: The final step in the breeding program is to develop a breeding strategy to propagate the edited traits. This could involve selecting edited animals with the desired traits and breeding them with other edited animals, or with non-edited animals to introduce the edited traits into a broader population. It's important to carefully monitor the breeding program to ensure the edited traits are being passed down successfully and that there are no unintended consequences (Wang et al., 2022; Whitworth et al., 2022).
- Evaluation of the results: The animals produced should be evaluated to determine if they meet the desired traits and are healthy.
- Establish regulations: There may be regulatory requirements for gene-edited animals, and the breeding program should be designed to comply with these regulations.

Generally, designing a breeding program for gene-edited animals requires careful planning and execution. It's essential to identify the desired traits, choose the appropriate gene-editing technique, screen and select edited animals, and develop a breeding strategy to propagate the edited traits successfully. Additionally, it's essential to adhere to ethical and regulatory guidelines to ensure the safety and well-being of the animals involved in the breeding program.

5. Policy for Genome Editing

The use of genome editing in livestock raises important ethical, safety, and regulatory issues, which require appropriate policy frameworks (Kumar and Kues, 2023). Policies for genome editing in livestock should balance the potential benefits of this technology with the potential risks and ethical concerns (Zhang et al., 2020). One key issue to consider is the safety of gene-edited animals for human consumption (Van Eenennaam and Young, 2019). Regulators must ensure that any gene-edited animals intended for food production are safe to consume and do not pose any risks to human health. Another important issue is the welfare of the animals themselves (Ormandy et al., 2011). Genome editing should be used to improve animal welfare (Kramer and Meijboom, 2021), not to create animals that suffer from unintended consequences or health issues. Policies for genome editing in livestock should also consider the potential environmental impacts (Gordon et al., 2021) of gene-edited animals. For example, gene-edited animals may have different interactions with their ecosystems, which could have unintended consequences on the environment. In terms of ethical concerns, policies for genome editing in livestock should consider the potential for unintended consequences or the creation of animals with characteristics that are viewed as undesirable or unethical. This could include concerns related to animal welfare, social acceptance, and cultural values (Eriksson et al., 2018; Gordon et al., 2021). Overall, policies for genome editing in livestock should be based on a careful consideration of the potential risks and benefits of this technology. They should be informed by scientific evidence, ethical considerations, and stakeholder engagement. The policies should also be flexible enough to accommodate new developments and emerging issues, while ensuring the safety of consumers, animals, and the environment.

6. Conclusion

Genome editing has the potential to sustain and revolutionize livestock production by improving animal welfare, productivity, and resilience to various stresses (heat, water and diseases). The technology can be used to develop animals with desirable traits, such as disease resistance, heat tolerance, and water use efficiency, among others. In the future, genome editing in livestock is likely to become more common, as the technology becomes more efficient, precise, and accessible. However, there are still significant challenges and uncertainties associated with the use of genome editing in livestock. These include issues related to safety, regulatory frameworks, ethical concerns, and public acceptance. Thus, further research is needed to fully understand the potential benefits and risks of genome editing in livestock.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	K.N.
C	100
D	100
S	100
L	100
W	100
CR	100
SR	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

References

Alamer M. 2011. The role of prolactin in thermoregulation and water balance during heat stress in domestic ruminants. Asian J Anim Vet Adv, 6(12): 1153-1169.

Anderson R, Bayer PE, Edwards D. 2020. Climate change and the need for agricultural adaptation. Current Opin Plant Biol, 56: 197-202.

Bahbahani H, Musa HH, Wragg D, Shuiep ES, Almathen F, Hanotte O. 2019. Genome diversity and signatures of selection for production and performance traits in dromedary camels. Frontiers Genet, 10: 893.

Bunton-Stasyshyn RK, Codner GF, Teboul L. 2022. Screening and validation of genome-edited animals. Lab Anim, 56(1): 69-82.

Cole JB. 2019. Promotion of alleles by genome engineering. CABI Reviews, 2019: 1–15.

Dunne JC, O'Connell J, McMahon BJ, Chase CC, Halloran AM, Doyle DN, Kenny DA. 2019. Genome editing for reduction of methane emissions in ruminants: Opportunities challenges. Meat Sci, 154: 92-99.

Durosaro SO, Iyasere OS, Ilori BM, Oyeniran VJ, Ozoje MO. 2023. Molecular regulation, breed differences and genes involved in stress control in farm animals. Domestic Anim Endocrinol, 82: 106769.

Ellen MacArthur Foundation. 2021. Circular Economy in Cities: Evolving the Model for a Sustainable Urban Future. URL: https://www.ellenmacarthurfoundation.org/publications/circular-economy-in-cities-evolving-the-model-for-a-sustainable-urban-future (access date: September 17, 2021).

Eriksson S, Jonas E, Rydhmer L, Röcklinsberg H. 2018. Invited review: Breeding and ethical perspectives on genetically modified and genome edited cattle. J Dairy Science, 101(1): 1-17.

FAO. 2014. Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. URL: http://www.fao.org/3/a-i3437e.pdf (access date: September 17, 2021).

Gaudry MJ, Charlesworth CT, Pagella P, Sánchez JM, Robinson ME, Wallner G, Lillico SG. 2021. Genome-edited pigs give birth to piglets with resistance to African swine fever virus. Nature Biotechnol, 39(6): 773-774.

Gordon DR, Jaffe G, Doane M, Glaser A, Gremillion TM, Ho MD. 2021. Responsible governance of gene editing in agriculture and the environment. Nature Biotechnol, 39(9): 1055-1057.

Gori JL, Hsu PD, Maeder ML, Shen S, Welstead GG, Bumcrot D. 2015. Delivery and specificity of CRISPR/Cas9 genome editing technologies for human gene therapy. Human Gene Therap, 26(7): 443-451.

Guo C, Wang M, Zhu Z, He S, Liu H, Liu X, Shi X, Tang T, Yu P, Zeng J. 2019. Highly efficient generation of pigs harboring a partial deletion of the CD163 SRCR5 domain, which are fully resistant to porcine reproductive and respiratory syndrome virus 2 infection. Front Immunol, 10: 1846.

Haire A, Bai J, Zhao X, Song Y, Zhao G, Dilixiati A, Li J, Sun WQ, Wan P, Fu X. 2022. Identifying the heat resistant genes by multi-tissue transcriptome sequencing analysis in Turpan Black sheep. Theriogenology, 179: 78-86.

Hill GM, Gifford CA, Zimmerman S. 2021. Livestock Genomics for Mitigating Climate Change. Annual Rev Anim Biosci, 9: 95-121.

IEA. 2020. Energy Technology perspectives 2020. URL: https://www.iea.org/reports/energy-technology-perspectives-2020 (access date: September 17, 2021).

Jahan K, Nie H, Yin Z, Zhang Y, Li N, Yan X. 2022. Comparative transcriptome analysis to reveal the genes and pathways associated with adaptation strategies in two different populations of Manila clam (Ruditapes philippinarum) under acute temperature challenge. Aquaculture, 552: 737999.

Jasrotia R, Dhar M, Langer S. 2023. Climate change impacts on animal production. In Ahmed M, editor. Global Agricultural Production: Resilience to Climate Change, Springer, London, UK, pp: 311-333.

Karavolias NG, Horner W, Abugu MN, Evanega SN. 2021. Application of gene editing for climate change in agriculture. Front Sustain Food Systems, 5: 685801.

Khalil AM. 2020. The genome editing revolution. J Genet Engin Biotechnol, 18(1): 1-16.

Khiabani A, Kohansal MH, Keshavarzi A, Shahraki H, Kooshesh M, Karimzade M, Gholizadeh Navashenaq J. 2023. CRISPR/Cas9, a promising approach for the treatment of β-thalassemia: A systematic review. Molec Genet Genom, 298(1): 1-11.

Kramer K, Meijboom FLB. 2021. Using breeding technologies to improve farm animal welfare: What is the ethical relevance of telos? J Agri Environ Ethics, 34(1): 2.

Kumar D, Kues WA. 2023. Genome engineering in livestock: Recent advances and regulatory framework. Anim Reprod Update, 3(1): 14-30.

Lea AJ, Caldas IV, Garske KM, Echwa J, Gurven M, Handley C, Kahumbu J, Kamau J, Kinyua P, Lotukoi F. 2023. Adaptations to water stress and pastoralism in the Turkana of northwest Kenya. BioRxiv, 2021-2023.

Leisner CP. 2020. Climate change impacts on food security-focus on perennial cropping systems and nutritional value. Plant Sci, 293: 110412.

Li T, Yang Y, Qi H, Cui W, Zhang L, Fu X, He X, Liu M, Li P, Yu T. 2023. CRISPR/Cas9 therapeutics: progress and prospects. Signal Transduct Targeted Therap, 8(1): 36.

Liu J, Wang Y, Du Y, Zhou J, Ye K, Li J, Zhang Q. 2019. Targeted mutagenesis of the porcine endogenous retrovirus sequences in the pig genome to improve xenotransplantation outcomes. Cell Transplant, 28(11): 1415-1427.

Liu Y, Huang J, Ma X, Wei S, Qiu Q, Wang G, Wu Z. 2020. Overexpression of HSF1 enhances thermotolerance in porcine cells. Sci Reports, 10(1): 1-10.

Matres JM, Hilscher J, Datta A, Armario-Nájera V, Baysal C, He W, Huang X, Zhu C, Valizadeh-Kamran R, Trijatmiko KR. 2021. Genome editing in cereal crops: an overview. Transgenic Res, 30: 461-498.

Mehra VK, Kumar S. 2022. The application of CRISPR/Cas9 technology for farm animals: a review. Agri Rev, 43(1): 54-61.

Menz J, Modrzejewski D, Hartung F, Wilhelm R, Sprink T. 2020. Genome edited crops touch the market: a view on the global development and regulatory environment. Front Plant Sci, 11: 586027.

Moloney AP, McGee M. 2023. Factors influencing the growth of meat animals. In Toldra F, editor. Lawrie's Meat Science, Elsevier, London, UK, pp: 21-49.

Mueller JP, Rischkowsky B, Haile A, Philipsson J, Mwai O, Besbes B, Valle Zárate A, Tibbo M, Mirkena T, Duguma G. 2015. Community-based livestock breeding programmes: essentials and examples. J Anim Breed Genet, 132(2): 155-168.

Mushtaq M, Molla KA. 2023. Principles of genome editing and its applications in fisheries. In Lakra WS, Goswami M, Trudeau VL, editors. Frontiers in Aquaculture Biotechnology.

Elsevier, London, UK, pp: 147-154.
Ngeno K, Omasaki S, Babe B. 2013. Assessment of the vulnerability and adaptation strategies to climate variability and change of the *bos taurus* dairy genotypes under diverse production environments in Kenya. J Vet Adv, 3(7): 186-196.
Ngeno K. 2015. Breeding program for indigenous chicken in Kenya. PhD thesis, Wageningen University, Wageningen, Holland, pp: 154.
Ormandy EH, Dale J, Griffin G. 2011. Genetic engineering of animals: Ethical issues, including welfare concerns. Canadian Vet J, 52(5): 544.
Panda SK, McGrew MJ. 2022. Genome editing of avian species: implications for animal use and welfare. Lab Anim, 56(1): 50-59.
Park TS. 2023. Gene-editing techniques and their applications in livestock and beyond. Korea, 7: 8.
Pazhany AS, Henry RJ. 2019. Genetic modification of biomass to alter lignin content and structure. Indust Engin Chem Res, 58(35): 16190-16203.
Poore J, Nemecek T. 2018. Reducing food's environmental impacts through producers and consumers. Sci, 360(6392): 987-992.
Pramod, R. K, Mitra, A. 2023. Genome editing: A potential tool for enhancing livestock production. In Ravindra Pratap Singh RP, Adetunji CO, Singh RL, Singh J, Solanki PR, Singh KRB editors. Nanobiotechnology for the Livestock Industry, Elsevier, London, UK, pp: 277-300.
Ranjitha HB, Ramesh M, Behera S, ValiyaValappil D, Basagoudanavar SH, Sherasiya A. 2022. Genetic engineering tools and techniques in livestock production. In Yata VK, Mohanty AK, Lichtfouse E, editors. Sustainable Agriculture Reviews 57: Animal Biotechnology for Livestock Production 2. Springer, London, UK, pp: 175-207.
Rasheed A, Barqawi AA, Mahmood A, Nawaz M, Shah AN, Bay DH, Alahdal MA, Hassan MU, Qari SH. 2022. CRISPR/Cas9 is a powerful tool for precise genome editing of legume crops: a review. Molec Biol Reports, 49(6): 5595-5609.
Raza SHA, Hassanin AA, Pant SD, Bing S, Sitohy MZ, Abdelnour SA, Alotaibi MA, Al-Hazani TM, Abd El-Aziz AH, Cheng G. 2022. Potentials, prospects and applications of genome editing technologies in livestock production. Saudi J Biol Sci, 29(4): 1928-1935.
Rexroad C, Vallet J, Matukumalli LK, Reecy J, Bickhart D, Blackburn H, Boggess M, Cheng H, Clutter A, Cockett N. 2019. Genome to phenome: improving animal health, production, and well-being-a new USDA blueprint for animal genome research 2018-2027. Frontiers Genet, 10: 327.
Ricroch A. 2019. Global developments of genome editing in agriculture. Transgenic Res, 28: 45-52.
Roell MS, Zurbriggen MD. 2020. The impact of synthetic biology for future agriculture and nutrition. Current Opin Biotechnol, 61: 102-109.
Rossi L. 2020. CRISPR/Cas9-mediated UCP1 knock-in endows cattle with increased thermogenic capacity in brown adipose tissue. Sci Reports, 10(1): 1-10.
Sakadevan K, Nguyen ML. 2017. Livestock production and its impact on nutrient pollution and greenhouse gas emissions. Adv Agro, 141: 147-184.
Tang L, Xiang Q, Xiang J, Li J, Chen D. 2021. A variant in the 3'-untranslated region of the MC2R gene decreases the risk of schizophrenia in a female Han Chinese population. J Inter Med Res, 49(7): 03000605211029504.
Tian Y, Lei L, Zhu X, Xu J, Cui J, Zhang Z, Ma J. 2019. Knockout of TRPM8 alleviates dairy cow's heat stress by improving the systemic calcium status and the function of the rumen epithelium barrier. J Dairy Sci, 102(9): 7943-7953.
Van Eenennaam AL, Young AE. 2019. Gene editing in livestock: promise, prospects and policy. CABI Rev, 2018: 1-14.
Wang S, Qu Z, Huang Q, Zhang J, Lin S, Yang Y, Meng F, Li J, Zhang K. 2022. Application of gene editing technology in resistance breeding of livestock. Life, 12(7): 1070.
Wani AK, Akhtar N, Singh R, Prakash A, Raza SHA, Cavalu S, Chopra C, Madkour M, Elolimy A, Hashem NM. 2023a. Genome centric engineering using ZFNs, TALENs and CRISPR-Cas9 systems for trait improvement and disease control in Animals. Vet Res Communicat, 47(1): 1-16.
Wani AK, Akhtar N, Singh R, Prakash A, Raza SHA, Cavalu S, Chopra C, Madkour M, Elolimy A, Hashem NM. 2023b. Genome centric engineering using ZFNs, TALENs and CRISPR-Cas9 systems for trait improvement and disease control in Animals. Vet Res Communicat, 47(1): 1-16.
Whitworth KM, Green JA, Redel BK, Geisert RD, Lee K, Telugu BP, Wells KD, Prather RS. 2022. Improvements in pig agriculture through gene editing. CABI Agri Biosci, 3(1): 1-16.
Wray-Cahen D, Bodnar A, Rexroad C, Siewerdt F, Kovich D. 2022. Advancing genome editing to improve the sustainability and resiliency of animal agriculture. CABI Agri Biosci, 3(1): 1-17.
Yin K, Qiu JL. 2019. Genome editing for plant disease resistance: applications and perspectives. Philosoph Transact Royal Soc B, 374(1767): 20180322.
Yu H, Liu C, Dixon RA. 2021. A gene-editing/complementation strategy for tissue-specific lignin reduction while preserving biomass yield. Biotechnol Biofuels, 14(1): 1-12.
Zhang A, Yu J, Yan S, Zhao X, Chen C, Zhou Y, Zhao X, Hua M, Wang R, Zhang C. 2018. The genetic polymorphism and expression profiles of NLRP3 inflammasome in patients with chronic myeloid leukemia. Human Immunol, 79(1): 57–62.
Zhang D, Hussain A, Manghwar H, Xie K, Xie S, Zhao S, Larkin RM, Qing P, Jin S, Ding F. 2020. Genome editing with the CRISPR-Cas system: an art, ethics and global regulatory perspective. Plant Biotechnol J, 18(8): 1651-1669.
Zhao J, Lai L, Ji W, Zhou Q. 2019. Genome editing in large animals: current status and future prospects. National Sci Rev, 6(3): 402-420.