

Research Article

# Balancing Genetic Improvement with Conservation of Biodiversity a Review

Danayit Alem\* , Helen Aklilu 

Ethiopian Institute of Agricultural Research, Holetta Research Center, Addis Ababa, Ethiopia

## Abstract

Genetic improvement in livestock has played a crucial role in enhancing productivity and generating economic benefits worldwide. However, intensive selection for high-yield traits has often led to a reduction in genetic diversity and the erosion of indigenous breeds, thereby compromising ecological resilience and long-term sustainability. This review critically examines the dual challenge of achieving rapid genetic gains while preserving the biodiversity essential for adaptive capacity in livestock populations. By synthesizing recent advances in genomic technologies—including genomic selection and CRISPR/Cas9 gene editing with traditional breeding methods that emphasize the conservation of local genetic resources, the paper highlights the unique adaptive traits inherent in indigenous breeds. Special attention is given to sustainable breeding programs, effective policy interventions, and community-based conservation strategies as integral components of a balanced approach. The analysis outlines a comprehensive framework that reconciles the demands of enhanced productivity with the imperative of biodiversity preservation, ultimately supporting both economic development and environmental stewardship. This integrated perspective offers valuable insights for researchers, policymakers, and industry stakeholders striving to implement sustainable livestock systems in the face of global challenges.

## Keywords

Biodiversity, Conservation, Genetic Improvement, Indigenous Breeds

## 1. Introduction

Genetic improvement in livestock has been a cornerstone of agricultural development, driving significant gains in productivity, disease resistance, and economic returns. These advancements have played a critical role in addressing global food security challenges, particularly in the face of a growing population and changing climate [1]. However, the pursuit of genetic improvement has often come at the cost of biodiversity, as the focus on high-yield breeds has led to the marginalization of indigenous breeds and the erosion of genetic diversity [2]. This loss of biodiversity undermines the resilience of livestock systems, making

them more vulnerable to emerging diseases, climate variability, and environmental degradation [3].

The conservation of biodiversity is not merely an ecological concern but a necessity for sustainable agriculture. Indigenous livestock breeds, with their unique adaptive traits such as drought tolerance, disease resistance, and ability to thrive in harsh environments, are invaluable resources for maintaining ecological balance and ensuring long-term food security [4]. Despite their importance, these breeds are increasingly at risk of extinction due to the widespread adoption of exotic, high-yield breeds and the

\*Corresponding author: danay7521@gmail.com (Danayit Alem)

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lack of supportive policies and conservation efforts [5].

This review explores the intricate balance between genetic improvement and biodiversity conservation, emphasizing the need for strategies that sustain both productivity and ecological integrity. By examining the roles of indigenous breeds, advanced genomic tools, and sustainable breeding practices, this paper highlights how genetic improvement can coexist with biodiversity conservation [6]. The integration of these approaches is essential for building resilient livestock systems capable of addressing the challenges of the 21st century, from climate change to global food security [7].

## 2. Current Trends in Genetic Improvement

### 2.1. Advances in Breeding Programs

Modern breeding programs leverage advanced techniques like artificial insemination, embryo transfer, and marker-assisted selection to enhance desirable traits in livestock. The advent of genomic selection and CRISPR-based gene editing has revolutionized precision breeding, enabling targeted improvement with minimal generational lag. Genome editing tools such as CRISPR/Cas9 provide unprecedented precision in modifying specific genetic traits, significantly advancing livestock production by improving disease resistance, performance, and animal welfare [8]. Additionally, [9] highlight the versatility of CRISPR/Cas systems, noting

their efficiency, cost-effectiveness, and applicability across multiple species, including livestock, to achieve complex genetic improvements quickly. These technologies not only improve productivity but also align with sustainable agricultural practices by enhancing genetic diversity and resilience. However, ethical considerations and societal acceptance are crucial for widespread adoption, as these innovations reshape livestock breeding on a global scale.

### 2.2. Global Dominance of High-Yield Breeds

High-yield breeds, such as Holstein-Friesians in dairy production, dominate global markets due to their superior productivity. However, the focus on a limited number of breeds has led to genetic homogenization, which significantly increases vulnerability to diseases and environmental changes. Studies have emphasized that reliance on genetically uniform populations reduces adaptability to evolving pathogens and climate variability. For example, conservation efforts for indigenous and rare breeds, which often possess unique genetic traits conferring resilience, are highlighted as critical for maintaining biodiversity in livestock systems [1]. Additionally, researchers advocate for sustainable breeding practices that integrate diverse genetic resources to enhance both productivity and ecological stability [6]. Addressing these challenges requires a balance between exploiting high-yield breeds and conserving genetic diversity to ensure long-term agricultural sustainability.

*Table 1. Technological Innovations in Livestock Genetic Improvement.*

Technology	Application	Benefits	Challenges
CRISPR/Cas9	Gene editing for disease resistance, performance, and animal welfare.	High precision, cost-effectiveness, and versatility.	Ethical concerns and societal acceptance.
Genomic Selection	Identifying desirable traits using genomic data.	Faster genetic gain and reduced generation intervals.	Requires advanced infrastructure and expertise.
Artificial Insemination	Enhancing desirable traits through controlled breeding.	Improved productivity and genetic diversity.	Limited access to technology in low-income regions.
Embryo Transfer	Accelerating genetic improvement by transferring embryos from high-yield breeds.	Rapid dissemination of superior genetics.	High cost and technical complexity.

## 3. Impacts of Genetic Improvement on Biodiversity

### 3.1. Erosion of Indigenous Breeds

Indigenous breeds, often well-adapted to local environ-

ments and resistant to endemic diseases, are increasingly marginalized due to the introduction of high-yield exotic breeds. For example, in many regions of Africa and Asia, traditional cattle breeds are being replaced, leading to a significant loss of genetic diversity and adaptability. [3] emphasize the unique traits of indigenous livestock, such as disease resistance and adaptability to harsh climates, which are essential for sustainable farming systems [3]. Similarly, [4] highlights the urgent need to preserve local cattle breeds,

noting their ecological and cultural importance in maintaining biodiversity and resilience [4]. Conservation strategies, including pure breeding programs and policies promoting the use of native breeds, are critical to prevent extinction and ensure the continued availability of these invaluable genetic resources.

### 3.2. Loss of Adaptive Traits

Narrowing genetic diversity reduces the pool of adaptive traits essential for resilience against challenges such as emerging diseases or climate variability. Studies have shown that genetic diversity is critical for ensuring the adaptability of species to changing environmental conditions and the unpredictability of pathogen evolution. For example, indigenous livestock breeds often harbor genetic traits that enhance resistance to specific diseases and stressors, making them invaluable in sustainable breeding programs [3]. Similarly, [4] emphasizes that preserving genetic diversity in livestock is not only a safeguard against potential threats but also a cornerstone for ecological and agricultural sustainability. Conservation initiatives and targeted breeding strategies are ur-

gently needed to maintain and utilize this diversity effectively, ensuring resilience in food systems.

### 3.3. Ecosystem Imbalances

Reduced livestock biodiversity can disrupt ecosystem services such as nutrient cycling, soil fertility, and pest control, thereby undermining agricultural sustainability. [7] emphasize that native livestock breeds contribute significantly to ecosystem services, including soil improvement and ecological balance, compared to exotic breeds raised in intensive systems. These breeds are associated with provisioning, regulating, and cultural services that are crucial for sustainable food systems [7]. Further [10] highlight how biodiversity strengthens agricultural productivity by supporting key ecosystem functions such as pest control and nutrient recycling. Loss of biodiversity due to modern agricultural practices exacerbates environmental degradation, threatening long-term ecological resilience [10]. Sustainable livestock management, emphasizing native species and diverse agroecosystems, is essential to preserving these services and ensuring environmental and agricultural sustainability.

**Table 2.** Ecosystem Services: Indigenous vs. Exotic Livestock Breeds.

Ecosystem Service	Indigenous Breeds	Exotic Breeds
Nutrient Cycling	Contribute to soil fertility through natural grazing patterns	Often raised in intensive systems, leading to soil degradation.
Pest Control	Natural resistance to local pests reduces the need for chemical interventions.	Higher susceptibility to pests may increase reliance on pesticides.
Cultural Services	Linked to traditional practices and cultural heritage.	Lack cultural significance in local communities.
Adaptability	Well-adapted to local environmental conditions and climate variability.	Less adaptable to local conditions, requiring more resources for management.

## 4. Strategies for Balancing Genetic Improvement and Biodiversity Conservation

Reduced livestock biodiversity can disrupt ecosystem services such as nutrient cycling, soil fertility, and pest control, undermining agricultural sustainability.

### 4.1. Sustainable Breeding Programs

Sustainable breeding programs are vital for balancing genetic gain with economic, environmental, and societal sustainability in agriculture. In livestock systems, genomic selection technologies, such as those detailed by [11], show significant promise in tropical dairy farming. These ap-

proaches enhance genetic gain for traits like milk yield and reduce generation intervals, outperforming traditional progeny testing methods in economic and genetic efficiency [11]. Similarly, global beef and dairy genetics initiatives are adapting to climate and market demands through multi-trait selection indices, innovative reproductive techniques, and resource-efficient solutions, as demonstrated in the USA, Brazil, and Europe [12]. Crop breeding programs also exemplify sustainability by integrating wild relatives and traditional varieties to tackle emerging stresses. [13] highlight the importance of biodiversity in enhancing crop resilience and productivity, with successful examples in sunflowers and medicinal plants [13]. Further, innovations in plant factories demonstrate how breeding for improved yield and light-use efficiency can address environmental challenges in controlled agriculture [14].

These advances underscore the role of technological inte-

gration in achieving sustainable breeding, emphasizing tools like genomic selection, data platforms, and ecological adaptability to meet future food security and climate goals. Ethical and social dimensions must align with scientific advancements to ensure broad acceptance and lasting impact [15].

### 3.4. Conservation of Indigenous Breeds

The conservation of indigenous breeds is critical for preserving genetic diversity, cultural heritage, and the adaptability of animal populations to local environmental conditions. In South Africa, indigenous sheep breeds, such as the Damara and Zulu sheep, face challenges due to limited commercial interest and the need for greater awareness among farmers regarding their value. Conservation efforts focus on genetic and cultural preservation, emphasizing community-based breeding programs [5]. Similarly, in Ethiopia, sustainable utilization of indigenous cattle through genetic improvement strategies aims to enhance resilience to climate change while maintaining adaptive traits such as disease resistance and

tolerance to low-quality diets [16].

Sub-Saharan Africa presents unique challenges for conserving indigenous chickens, including disease outbreaks and erosion of genetic resources due to reliance on commercial breeds. Innovative strategies, such as integrating stakeholder engagement and local farmer practices, are essential for promoting the sustainable use of these breeds [17]. Jordan's efforts to preserve its indigenous chickens highlight the importance of phenotypic and genetic diversity analysis, which provides a foundation for conservation and breeding programs to prevent extinction and enhance adaptability [18].

Conservation strategies in Turkey involve morphological characterization of the Eastern Anatolian Red cattle under ex-situ and in-situ conditions, ensuring biodiversity and creating sustainable livestock management practices. These efforts underline the necessity of local adaptation and resource-efficient breeding [19]. Overall, a combination of genetic improvement, community engagement, and targeted conservation programs is vital for sustaining indigenous breeds globally.

*Table 3. Trade-offs and Synergies: Genetic Improvement vs. Biodiversity Conservation.*

Aspect	Trade-offs	Synergies
Genetic Diversity	Narrowing of genetic base due to focus on high-yield breeds.	incorporation of indigenous breeds to enhance genetic diversity.
Adaptive Traits	Loss of adaptive traits (e.g., disease resistance, climate tolerance).	Preservation of adaptive traits through conservation breeding programs.
Ecosystem Services	Disruption of ecosystem services (e.g., nutrient cycling, pest control).	Indigenous breeds contribute to ecosystem services (e.g., soil fertility).
Economic Productivity	Short-term gains from high-yield breeds may overshadow long-term sustainability.	Niche markets for indigenous breed products create economic incentives.
Cultural Heritage	Erosion of cultural and traditional practices linked to indigenous breeds.	Conservation of indigenous breeds preserves cultural heritage.

### 4.2. Policy Interventions

Indigenous breeds are crucial, as these breeds often carry unique genetic traits that are vital for resilience to local environmental challenges and diseases. For instance, in South Africa, government initiatives have highlighted the importance of financial and technical support to ensure the preservation of indigenous sheep breeds, which are often overlooked by commercial farmers [5]. Enforcing regulations to prevent genetic homogenization is equally essential, as unplanned crossbreeding and the dominance of commercial breeds threaten the genetic diversity of local populations. For

example, in Ethiopia, the unregulated replacement of indigenous cattle with exotic breeds has been identified as a major factor in the loss of adaptive traits critical for surviving climate extremes [16]. Additionally, governments must prioritize and fund research focused on biodiversity-friendly genetic improvement, such as genomic selection techniques that enhance productivity without compromising adaptive traits. Studies on indigenous chickens in Sub-Saharan Africa emphasize the role of targeted breeding programs in preserving genetic resources while promoting sustainability in rural farming systems [17]. Collectively, these measures ensure the long-term viability of indigenous breeds, contributing to global food security and ecological balance.

**Table 4.** Policy Interventions for Conserving Livestock Biodiversity.

Policy Intervention	Objective	Implementation Challenges	Outcome
Financial and Technical Support	Preserve indigenous breeds through funding and technical assistance.	Limited funding and lack of political commitment.	Improved conservation efforts in regions like South Africa.
Regulations on Cross-breeding	Prevent genetic homogenization by regulating unplanned crossbreeding.	Enforcement challenges and resistance from commercial farmers.	Reduced genetic erosion in Ethiopia and other regions.
Research Funding	Promote biodiversity-friendly genetic improvement (e.g., genomic selection).	Competing research priorities and limited resources.	Enhanced productivity and conservation of indigenous breeds.
Certification Schemes	Create niche markets for indigenous breed products (e.g., geographic indicators).	Lack of awareness among consumers and farmers.	Increased market value and economic incentives for conservation in Jordan.

### 4.3. Community Participation

Engaging local communities ensures the sustainable use and conservation of indigenous breeds by fostering a sense of ownership and responsibility. Traditional knowledge about breed management, including insights into breeding practices, disease resistance, and adaptation to local environmental conditions, can complement scientific approaches to conservation. For instance, in Sub-Saharan Africa, small-scale farmers play a pivotal role as custodians of indigenous chicken breeds, with their traditional practices offering critical insights for developing sustainable breeding programs [17]. Similarly, studies in South Africa have highlighted how community-based breeding initiatives can integrate traditional knowledge with advanced genetic improvement techniques to address challenges such as genetic erosion and market pressures [5]. By incorporating local expertise into policy and program design, governments and researchers can enhance the effectiveness of conservation strategies, ensuring these breeds remain viable and valuable for future generations.

### 4.4. Integrating Biodiversity into Market Systems

Promoting niche markets for products from indigenous breeds can create significant economic incentives for their conservation by leveraging their unique qualities and cultural heritage. Certification schemes, such as geographic indicators, not only enhance the market value of these products but also provide a framework for sustainable practices. For instance, in Jordan, initiatives to promote products derived from indigenous chickens have demonstrated that consumers are willing to pay a premium for products linked to traditional and environmentally friendly farming systems [18]. Similarly, studies on indigenous cattle in Turkey, such as the Eastern Anatolian Red breed, emphasize that branding and certification linked to local provenance can boost the demand for high-quality, sustainably produced meat and dairy products [19]. By link-

ing conservation efforts with economic benefits, niche markets and certification schemes ensure that indigenous breeds remain an integral part of sustainable agricultural systems.

## 5. Case Studies

### 5.1. The Boran Cattle of East Africa

Boran cattle, indigenous to East Africa, are renowned for their exceptional drought tolerance, disease resistance, and adaptability to harsh environmental conditions. Crossbreeding programs incorporating Boran genetics have successfully enhanced productivity traits, such as growth rate and milk yield, while preserving their valuable adaptive traits. For example, studies in Kenya have demonstrated that crossbreeding Boran cattle with exotic breeds has significantly improved meat and milk production without compromising their resilience to local climatic and disease challenges [20]. Additionally, the utilization of Boran genetics in Ethiopia has shown promising results in maintaining genetic diversity while optimizing livestock productivity under smallholder farming systems [21]. These initiatives underscore the importance of leveraging indigenous genetic resources like Boran cattle to sustainably meet increasing food demands in the face of climate change.

### 5.2. India's Indigenous Poultry Breeds

The Kadaknath breed, indigenous to India, is renowned for its high nutritional value, particularly its protein-rich and low-fat meat, as well as its exceptional disease resistance. These unique traits have led to increased market demand, encouraging conservation through commercialization and innovative farming practices. For instance, recent studies in Madhya Pradesh have highlighted the success of community-driven Kadaknath farming projects that not only boost rural incomes but also enhance breed conservation by linking production with certification and geographic indication status

[22]. Furthermore, the integration of Kadaknath farming into urban markets through e-commerce platforms has provided farmers with better pricing and broader reach, further incentivizing sustainable management of this breed [23]. These efforts illustrate how commercialization strategies can align economic benefits with biodiversity conservation.

### 5.3. Global Gene Banks

Initiatives such as the Global Databank for Animal Genetic Resources and FAO's Domestic Animal Diversity Information System (DAD-IS) have been instrumental in preserving livestock genetic diversity by providing comprehensive data collection, monitoring, and policy support frameworks. The DAD-IS platform, managed by FAO, offers a

global repository of information on livestock breeds, enabling countries to identify at-risk breeds and develop tailored conservation strategies. Recent updates to DAD-IS have incorporated advanced tools for tracking genetic diversity and assessing the impact of climate change on livestock populations, significantly enhancing its utility [24]. Similarly, the Global Databank consolidates genetic resource data from various countries, fostering international collaboration and guiding the sustainable use of these resources. Reports suggest these systems have facilitated the successful conservation of endangered breeds by linking genetic data with actionable conservation programs, as observed in regions like Sub-Saharan Africa and South Asia [25]. These initiatives underscore the importance of data-driven approaches to safeguard livestock biodiversity for future generations.

*Table 5. Case Studies of Conservation of Indigenous Livestock Breeds.*

Breed	Region	Conservation Strategy	Outcome
Boran Cattle	East Africa	Crossbreeding with exotic breeds to enhance productivity while preserving adaptive traits.	Improved meat and milk production without compromising resilience.
Kadaknath Chicken	India	Community-driven farming projects linked to certification and niche markets.	Increased rural incomes and enhanced breed conservation.
Damara Sheep	South Africa	Community-based breeding programs and awareness campaigns.	Improved conservation status and genetic preservation.
Eastern Anatolian Red	Turkey	Morphological characterization and ex-situ/in-situ conservation.	Sustainable livestock management and biodiversity preservation.
Zulu Sheep	South Africa	Genetic and cultural preservation through community engagement.	Enhanced adaptability and market value of indigenous breeds.

## 6. Challenges and Future Directions

### 6.1. Challenges

Conservation-focused programs face significant challenges, including limited funding, insufficient awareness among stakeholders about biodiversity's importance, and conflicts between short-term economic productivity and long-term sustainability goals (Table 6). Limited funding is often a consequence of competing financial priorities and a lack of political commitment to allocate resources for conservation. This underfunding impairs critical activities such as habitat restoration, wildlife protection, and community-based conservation efforts, disproportionately affecting biodiversity hotspots in low-income regions. Moreover, stakeholder awareness remains a critical bottleneck; without recognizing the intrinsic and utilitarian value of biodiversity, support for conservation initiatives tends to wane. Campaigns aimed at educating policymakers, businesses, and local communities

about ecosystem services such as carbon sequestration, water purification, and pollination are essential to bridging this gap. Additionally, conflicts arise from prioritizing short-term gains, such as agricultural expansion or industrial development, which often result in habitat loss and species extinction. Long-term sustainability demands integrated approaches that align economic incentives with conservation goals, such as payments for ecosystem services, eco-certifications, and biodiversity offsets. Recent frameworks, like the post-2020 Global Biodiversity Framework under the Convention on Biological Diversity (CBD), emphasize these intersections, calling for transformative changes in policy and financing mechanisms.

### 6.2. Future Directions

Recent advancements in genomic tools are revolutionizing agriculture for smallholder farmers, enabling the development of cost-effective solutions that enhance crop resilience and productivity. Innovations such as high-throughput genotyping services allow smaller breeding programs to access

world-class genotyping at reduced costs, facilitating rapid breeding of improved crop varieties tailored for local conditions (Frontiers in Plant Science, 2023). Additionally, genome editing technologies like CRISPR-Cas9 are being utilized to enhance traits such as climate resilience and nutritional value, addressing critical challenges in food security and sustainability [26]. This integrated approach combines genetics, ecology, and socioeconomics to create holistic strategies that empower farmers while promoting sustainable practices [27].

Furthermore, global collaborations are essential for sharing resources and knowledge, exemplified by initiatives that focus on improving livestock production through advanced genetics, which aim to bolster food security in vulnerable communities [28]. Overall, these efforts underscore the transformative potential of genomic innovations in supporting smallholder farmers and fostering agricultural sustainability worldwide.

**Table 6.** Challenges and Future Directions in Balancing Genetic Improvement and Biodiversity.

Challenge	Description	Future Direction
Limited Funding	Insufficient financial resources for conservation programs.	Increase funding through international collaborations and public-private partnerships.
Stakeholder Awareness	Lack of awareness about the importance of biodiversity.	Launch education campaigns targeting policymakers, farmers, and consumers.
Short-term vs. Long-term Goals	Conflict between immediate economic gains and long-term sustainability.	Develop integrated approaches (e.g., payments for ecosystem services).
Technological Adoption	Limited access to advanced technologies in low-income regions.	Promote cost-effective and accessible technologies for smallholder farmers.

## 7. Conclusion

Balancing genetic improvement with biodiversity conservation is not only essential for sustainable livestock production but also for ensuring food security and ecological resilience. By embracing innovative technologies, preserving indigenous breeds, and fostering inclusive policies, it is possible to achieve a harmonious relationship between productivity and biodiversity. This balance is crucial for addressing the challenges of the 21st century and safeguarding the future of livestock systems worldwide.

## Abbreviations

CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
FAO	Food and Agriculture Organization
DAD-IS	Domestic Animal Diversity Information System
CBD	Convention on Biological Diversity
GMO	Genetically Modified Organism

## Author Contributions

**Danayit Alem:** Conceptualization, Writing – original draft  
**Helen Aklilu:** Writing – review & editing

## Conflicts of Interest

The authors declare no conflicts of interest.

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