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ECONOMIC ASSESSMENT OF BEEF CATTLE GENOMIC SELECTION: A LITERATURE REVIEW

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Abstract
The beef cattle genome provides a vital foundation for exploring genetic variations that affect key traits, including growth, reproduction and disease resistance. Recent progress in genomic research has facilitated more accurate breeding approaches, promoting greater efficiency within beef production systems. The economic assessment of genome in beef cattle breeding has emerged as a pivotal area of research, offering pathways to enhance productivity, sustainability and profitability in the livestock industry. The study aims to consolidate current research on the economic implications of genomic selection. The research employs the descriptive and analysis-synthesis methods. Genomic selection has proven economically viable, reducing generation intervals, improving selection accuracy and identifying genetic markers linked to desirable traits. While the long-term economic benefits - such as enhanced feed efficiency, improved carcass quality and reduced environmental impacts - are well-documented, barriers like high initial investment costs, regional variability in production systems and the need for specialised data infrastructures remain significant challenges. Ethical considerations, evolving regulatory frameworks and the demand for traceable, high-quality beef further influence the adoption and implementation of genomic selection. This review underscores the need for targeted policy interventions, financial incentives and industry-wide collaboration to maximise the economic potential of genomic technologies in beef cattle breeding. Despite its potential, the high initial costs of genomic technologies and the need for robust data infrastructures remain significant challenges.
Keywords: beef cattle, genome, economic trait, genomic selection, profitability.

Introduction

The beef cattle industry plays a crucial role in meeting the global demand for high-quality protein while addressing sustainability and economic efficiency challenges. The application of genomic technologies has emerged as a transformative approach in breeding programmes, providing tools to enhance traits critical for economic and environmental outcomes (Boaitey et al., 2019; Gao et al., 2024). Genomic selection (GS), a technique that uses dense genetic markers across the genome, has shown the potential to improve selection accuracy and reduce generation intervals. For example, genomic selection has successfully accelerated genetic progress in traits such as feed efficiency, meat quality, and disease resistance (Gao et al., 2024; Romero et al., 2024). Holman & Hopkins (2021) state that by enabling early selection of breeding candidates based on genomic data, GS reduces costs and increases the reliability of breeding value predictions. Key economically significant traits of beef cattle include carcass weight, longissimus muscle area, backfat thickness, and marbling score. Park et al. (2013) emphasise that genomic determination would be a valuable tool in identifying relevant genetic markers for economically important traits in beef cattle. According to Holman and Hopkins, by enabling early selection of breeding candidates based on genomic data, GS reduces costs and increases the reliability of breeding value predictions. Key genome sequencing and assembly advancements have expanded genomics' utility in the industry. High-throughput sequencing technologies have enabled the identification of genes linked to economically significant traits, such as marbling, tenderness and environmental adaptability. As discussed in recent studies, the pan-genome approach provides insights into structural variations and rare alleles; thereby, enriching the understanding of genetic diversity. Consumer research indicates that European customers are willing to pay a premium for guaranteed eating quality, provided such assurance schemes are transparent and independently verified (Gao et al., 2024; Farmer & Farrel, 2018).

Consumer satisfaction is a key determinant of economic viability in the food production industry, particularly in the beef sector, where quality and consistency significantly influence purchasing behaviour, according to Hocquette et al. (2014). Despite considerable efforts to standardise and enhance beef quality, variability remains a persistent challenge, contributing to consumer dissatisfaction and, in some cases, a decline in demand. Strengthening consumer confidence through grading systems, traceability, and quality assurance schemes has yielded economic benefits by fostering customer loyalty and willingness to pay premium prices. Furthermore, integrating economic efficiency with environmental sustainability and animal welfare - through optimised feeding regimes, reduced pre-slaughter stress, and the application of genetic markers - can result in mutually beneficial outcomes for both producers and consumers. These strategies enhance meat palatability and nutritional value and improve market positioning by addressing contemporary health, safety, and sustainability concerns. As economic pressures and societal expectations continue to evolve, aligning production practices with consumer preferences remains critical for ensuring the long-term resilience and competitiveness of the industry.

The economic sustainability of beef enterprises has to be shaped by both geographical constraints and market dynamics, requiring producers to make strategic decisions that balance profitability with risk management. Following Bowen & Chudlegh (2021), each region has significant climatic variability, including unpredictable rainfall patterns, prolonged droughts, and extreme weather events, impacting pasture availability, herd productivity, and overall economic returns. In addition, the remoteness of many beef enterprises leads to high transport costs, limited market access, and increased operational expenses, further influencing financial viability. Economic frameworks incorporating farm-level modelling and discounted cash-flow analysis are essential in evaluating alternative management strategies, allowing producers to assess the long-term profitability, financial risks, and capital investment requirements associated with various interventions. Moreover, the ongoing disconnect between asset values and returns, alongside fluctuating commodity prices, necessitates a careful economic assessment of strategies such as herd restructuring, genetic improvements, and market diversification. By integrating economic principles with an understanding of geographical challenges, producers can enhance decision-making processes and improve the resilience of their enterprises against external shocks.

Some researchers emphasise that crossbreeding has long been utilised in the beef cattle industry to leverage heterosis for improved growth, reproductive traits, and economic efficiency. Hay & Roberts (2023) suggest that heterosis arises from non-additive genetic interactions often excluded in genetic evaluations. Advances in genomic technologies, including single nucleotide polymorphism (SNP) genotyping, allow detailed exploration of heterosis to quantify the effects of genomic heterozygosity on growth traits and identify genomic regions linked to dominance, ultimately contributing to economically beneficial crossbreeding practices. According to Popp et al. (2020), the economic performance of cow-calf operations is significantly influenced by genetic selection, forage management, and breed adaptability to environmental conditions. In regions where forage variability and climatic constraints challenge cattle production, optimising breeding strategies becomes essential for improving profitability and sustainability. The integration of genetic marker analysis in breeding decisions has been explored to enhance reproductive efficiency, growth rates and overall herd performance. However, the extent to which genetic markers contribute to economic returns remains controversial, particularly in environments characterised by fescue toxicosis and other forage-related stress factors. Economic modelling frameworks enable producers to evaluate the financial viability of different breeding and management strategies by considering factors such as breeding failure rates, weaning weights, and pasture quality. Insights into the role of genetic selection in optimising economic sustainability within the cow-calf sector are obtained by examining the interplay between genetic information, environmental conditions and financial outcomes.

The study aims to consolidate current research on the economic implications of genomic selection. To address the research aim, the study advances the following tasks: 1) to study the economic benefits of genomic selection, such as profitability and market competitiveness; 2) to review economic challenges in adoption and sustainability; 3) to state the role of emerging technologies.

The economic performance of the beef industry is increasingly linked to the quality of meat, which directly influences consumer preferences, pricing structures, and overall market demand. Given that beef tenderness, juiciness, and flavour play a crucial role in optimising meat quality through emerging technologies, nutritional interventions and management strategies have become a priority for producers. However, environmental variability, breed-specific genetic limitations, and the financial implications of dietary modifications challenge achieving economically viable quality levels. Advanced genomic selection, precision feeding strategies, and microbiome manipulation are key methods to improve quality while maintaining cost efficiency, according to Abebe et al. (2024). Moreover, implementing sustainable production systems that balance profitability with consumer expectations and regulatory frameworks is critical for ensuring long-term sector growth. By integrating economic principles with scientific advancements, the beef industry can enhance product quality, meet evolving market demands, and strengthen its competitive position in global trade.

Materials and Methods

The current study consolidates existing research, particularly on the economic assessment of the beef cattle genome, exploring genomic applications in areas such as meat quality selection, feed efficiency and disease resistance. The research employs descriptive and analysis-synthesis methods. Science Direct, Scopus and Ebsco databases were used to search for full-text articles in the English language published between 2013 and 2024. The following keywords and their combinations were used to narrow the search: beef cattle, economic effect, economic trait, genome, genomic selection, and genetic markers.

Results and Discussion

Economic Implications of Genomic Selection in Beef Production

Using genomic selection in beef cattle breeding and production offers substantial economic benefits, notably by improving breeding and production efficiency, enhancing production traits and meat quality, lowering costs and boosting overall profitability. By enabling precise identification of desirable traits such as feed efficiency, carcass quality, reproductive performance and disease resistance, genomic selection allows producers to optimise herd management strategies. Feed efficiency, in particular, is a key economic determinant, as feed costs represent one of the most significant expenses in beef production. Boaitey et al. (2019) indicate that studies have shown that genomic selection for improved feed conversion ratios can significantly lower feed intake per kilogram of weight gain, reducing overall production costs while maintaining or improving output levels. Beyond direct cost savings, genomic selection facilitates accelerated genetic progress, leading to cumulative economic benefits over successive generations. Unlike traditional selection methods, which rely on phenotypic evaluation and require multiple breeding cycles to achieve genetic improvements, genomic selection allows for earlier and more accurate identification of superior animals. This enables producers to make informed breeding decisions that enhance herd productivity and profitability (Gao et al., 2024). Furthermore, improvements in disease resistance through genomic selection reduce veterinary expenses and mortality rates, further contributing to cost efficiency. Following Ibtisham et al. (2017) observations, traditional breeding methods have relied heavily on phenotypic selection, which requires multiple generations to achieve noticeable improvements. Contrastingly, Mohammadiyeh et al. (2023) conclude that genomic selection allows producers to make earlier and more precise breeding decisions, reducing production costs and accelerating genetic progress. Gutierrez-Reinoso et al. (2021) indicate that one of the most economically significant applications of genomic selection is feed efficiency improvement, a major determinant of profitability in beef operations. Selecting animals with superior residual feed intake traits enables lower feed consumption while maintaining growth performance, leading to substantial cost savings. Besides, genomic selection for disease resistance lowers veterinary expenses, reduces mortality rates, and improves overall herd health, enhancing financial returns, acknowledge Mohammadiyeh et al. (2023). Consumer acceptance of beef, assert Holman & Hopkins (2021), is primarily determined by its sensory attributes, including tenderness, flavour, juiciness and overall palatability. Consequently, identifying and selecting genetic markers associated with these traits, highlighted by Romero et al. (2024), allows for a more precise and economically efficient approach to meat production. Genomic selection enables breeders to enhance desirable characteristics such as intramuscular fat composition, a critical determinant of meat quality and consumer preference. By improving the predictability of meat traits, genomic selection reduces production costs associated with prolonged feeding times and inefficient resource allocation. Furthermore, Abebe et al. (2024) indicate that intramuscular fat levels significantly impact carcass valuation in premium beef markets, where marbling is decisive in pricing, while Romero et al. (2024) acknowledge that the ability to select optimal intramuscular fat levels through genomic testing allows producers to enhance carcass quality without excessive feed costs. This economic benefit is particularly relevant in countries where consumers are willing to pay a premium for high-quality beef and have established grading systems based on intramuscular fat content. Farmer & Farrell (2018) observe that consumer preference for high-quality meat is well documented, with studies indicating a willingness to pay premium prices for products that meet stringent quality criteria. Genomic selection enables producers to align beef quality with consumer expectations, particularly regarding flavour, texture, and juiciness, key determinants of purchasing decisions. Incorporating genomic data into quality assurance schemes has demonstrated tangible financial benefits, with price premiums generated for verified high-quality beef.

Enhancing Profitability Through Genomic Selection for Growth and Reproductive Traits

From an economic perspective, genomic selection accelerates genetic improvement, leading to higher-quality carcasses in fewer generations. This reduces the cost of prolonged feeding and management, state Holman & Hopkins (2021), while increasing revenue through improved carcass grading and consumer satisfaction. Furthermore, Romero et al. (2024) identify that studies indicate that integrating genomic selection with conventional breeding methods significantly improves the accuracy of predicting meat quality traits, thereby reducing the economic risks associated with inefficient selection. Integrating genomic selection into breeding programmes enhances overall herd profitability by improving production efficiency and product quality. One of the primary advantages is improved reproductive efficiency, which is critical for economic viability in cow-calf operations. According to Gao et al. (2024), shorter calving intervals, higher fertility rates and increased calf crop percentages lead to more significant revenue potential while reducing input costs per output unit. Furthermore, genomic selection aligns production outputs with market demands by selecting genetic traits linked to superior carcass attributes, such as increased marbling and tenderness. Genomic selection improves growth performance, reproductive efficiency, and carcass traits, directly influencing economic sustainability. Studies on heterosis in crossbred populations conclude Hay & Roberts (2023) have demonstrated that selecting for genetic dominance effects can result in increased growth rates and higher carcass yields, leading to improved market value. Genomic analyses have identified SNPs associated with birth weight, weaning weight, and yearling weight, enabling targeted selection for superior growth traits and reducing variability in production outcomes. Enhancing reproductive performance through genomic selection is particularly beneficial in cow-calf operations, where fertility rates and calving intervals significantly affect profitability. By identifying genetic markers linked to higher fertility, reduced embryonic loss and improved calving ease, following Bowen & Chudleigh (2021), genomic selection helps producers optimise reproductive efficiency, ensuring consistent calf crops and higher revenue potential.

Economic Sustainability and Risk Management in Genomic Selection Adoption

Genomic selection also plays a crucial role in improving environmental sustainability, which has financial implications. Moreover, genomic selection is critical in environmental sustainability, which is increasingly linked to economic outcomes, suggest Hocquette et al. (2014), indicating that selecting cattle with higher feed conversion efficiency reduces feed costs and lowers methane emissions per kilogram of beef produced, aligning with evolving regulatory requirements and consumer-driven sustainability standards. Such improvements position genomic selection as a dual-benefit approach, enhancing profitability and environmental responsibility. Selecting for feed efficiency reduces input costs and minimises methane emissions per kilogram of beef produced. Following Gerber et al. (2013), methane emissions from enteric fermentation significantly contribute to agriculture-related greenhouse gas emissions, accounting for approximately 39% of total livestock emissions. By improving feed conversion efficiency, genomic selection contributes to lower environmental impact per production unit while supporting compliance with evolving sustainability standards. In jurisdictions where carbon offset schemes are implemented, state Boaitey et al. (2019), producers participating in genomic selection programmes can benefit from additional revenue streams through carbon credit trading. However, the extent to which these incentives drive adoption varies across regions due to differences in agroecological conditions and market structures. For carbon offset schemes to be effective, policy frameworks must account for spatial heterogeneity in breeding conditions and production systems.

Despite its clear advantages, adopting genomic selection presents particular challenges, primarily related to initial investment costs and knowledge barriers; thus, Mohammaddiyeh et al. (2023) conclude that genomic testing requires infrastructure and expertise in data analysis and breeding programme integration, which may be financially burdensome for small and medium-sized producers. However, Bowen & Chudleigh (2021) argue that economic modelling suggests that the long-term financial benefits, notably improved feed efficiency and higher carcass value, outweigh these initial costs. Another economic challenge is the integration of genomic selection into existing breeding programmes. While SNP-based selection significantly enhances the accuracy of trait prediction, the implementation process requires specialised knowledge and infrastructure, which may not be readily available in all production regions, as Romero et al. (2024) stated. In addition, Abebe et al. (2024) emphasise that genomic selection alone cannot guarantee economic success unless combined with optimal feeding regimes and stress-minimising management strategies. Genomic testing requires an initial investment in laboratory analysis and data interpretation, according to Romero et al. (2024), which may be a barrier for small and medium-sized beef enterprises. Furthermore, Holman & Hopkins (2021) state that environmental conditions influence the effectiveness of genomic selection, as intramuscular fat deposition is also affected by factors such as grazing strategies, feed composition, and climatic variability.

Market Competitiveness and Consumer Demand for Genomically Selected Beef

Genomic selection enhances market competitiveness by enabling beef production to meet regulatory and consumer-driven quality standards. Farmer & Farrel (2018) indicate that the European and North American beef industries face increasing consumer scrutiny regarding food safety, sustainability and traceability. Genomic selection supports traceability initiatives by providing genetic insights that link production practices to specific quality attributes. This, in turn, strengthens brand differentiation and allows producers to target niche markets where consumers prioritise ethically sourced, high-quality beef. Furthermore, genomic selection aligns with the growing emphasis on precision agriculture, wherein data-driven approaches optimise resource use and economic returns. By integrating genomic insights with farm management technologies, producers can implement breeding programmes that maximise efficiency while responding to shifting market demands. The ability to produce consistently high-quality beef enhances consumer trust and fosters brand loyalty, leading to long-term economic sustainability. Hocquette et al. (2014) emphasise that the economic benefits of genomic selection extend beyond production efficiency to market competitiveness and consumer demand. The beef industry increasingly integrates genomic technologies into quality assurance programmes using genetic insights to predict and ensure meat quality. Gutierrez-Reinoso et al. (2021) identify that incorporating genomic selection in these programmes strengthens brand differentiation, enhances consumer trust and secures higher price premiums for beef products that meet traceability and sustainability criteria. Moreover, genomic selection supports traceability and certification schemes, which are becoming critical in both domestic and export markets. Ibtisham et al. (2017) conclude that verifying genetic lineage, production history, and meat quality through genomic data gives producers a competitive advantage, particularly in premium markets where food safety, sustainability, and animal welfare concerns shape consumer purchasing decisions.

Economic Challenges and Adoption Considerations

Despite the clear economic benefits of genomic selection, several barriers to adoption persist. The initial investment in genomic testing and data analysis infrastructure can be substantial, particularly for small and medium-sized enterprises. Moreover, the benefits of genomic selection are not always immediately realised, as genetic improvements often require multiple breeding cycles before they translate into measurable economic gains. In addition, regional variations in production systems can influence the effectiveness of genomic selection strategies. An animal's genetic potential may not always be fully expressed in extensive grazing systems, where environmental factors such as forage availability and climate variability dominate. This underscores the importance of integrating genomic selection with adaptive management strategies that account for environmental constraints, according to Boaitey et al. (2019). Targeted policy interventions, financial incentives and producer education programmes are needed to facilitate broader adoption. Government subsidies for genomic testing, cost-sharing initiatives and knowledge transfer programmes can help mitigate adoption barriers and ensure that genomic selection technologies are accessible to a broader range of producers.

Role of Emerging Technologies in Beef Market Competitiveness

The global beef industry is increasingly adopting emerging technologies such as genomic selection, transcriptomics, metabolomics, and microbiome manipulation to enhance meat quality and economic sustainability, following Abebe et al. (2024). Genomic selection enables targeted breeding for enhanced intramuscular fat composition, reducing variability in meat quality and improving consistency across production systems. Furthermore, integrating microbiome profiling and metabolomic analysis has provided more profound insights into how microbial populations in the digestive system influence fat deposition and muscle development. Economic benefits arise from the ability to optimise nutritional strategies based on genetic predispositions. For example, nutritional interventions such as high-energy diets, omega-3 fatty acid supplementation and precision feeding techniques have enhanced intramuscular fat deposition, increasing meat quality scores and market value, conclude Abebe et al. (2024), stating that hormonal and dietary management strategies, including castration timing and early weaning protocols, have been identified as practical tools for optimising intramuscular fat composition, further reinforcing the economic rationale for precision management.

Genomic selection and emerging technologies represent transformative advancements in beef production, offering substantial economic benefits through improved meat quality, enhanced feed efficiency and increased market competitiveness. Genomic technologies enable precise selection for traits such as intramuscular fat composition, tenderness, and juiciness, aligning beef production with consumer preferences while reducing input costs. While adoption barriers remain, the long-term economic advantages of genomic selection far outweigh the initial investment costs. Genomic selection represents a transformative approach to beef cattle breeding, offering substantial economic benefits through enhanced feed efficiency, improved carcass quality and reduced environmental impact. While challenges related to adoption costs and regional variability persist, the long-term financial gains and market advantages underscore the importance of integrating genomic technologies into breeding programmes. Moving forward, the integration of genomic data with precision nutrition and management strategies will be critical in maximising the profitability and sustainability of the beef industry as well as collaboration between researchers, industry stakeholders, and policymakers will be crucial in maximising the economic potential of genomic selection in the beef sector. In conclusion, genomic selection presents a compelling economic opportunity for beef producers by improving efficiency, reducing costs and enhancing product quality. The beef industry can achieve long-term economic sustainability by integrating advanced genomic technologies with strategic breeding decisions while addressing environmental and consumer-driven market demands.

Conclusions

1. The application of genomic selection in beef cattle breeding has demonstrated significant economic benefits, including improved feed efficiency, enhanced carcass quality and increased reproductive performance. By enabling a more precise selection of economically valuable traits, genomic technologies contribute to higher profitability while supporting the sustainability of beef production systems.
2. Integrating genomic selection into beef production enhances product quality and consistency and strengthens market competitiveness. There is a growing demand for high-quality, traceable, and ethically produced beef, and genomic technologies offer a means to meet these expectations while securing premium pricing in domestic and export markets.
3. Genomic selection plays a crucial role in reducing the environmental footprint of beef production. Improving feed conversion efficiency and disease resistance reduces resource consumption and methane emissions. These advancements align with global sustainability targets and carbon offset initiatives, positioning genomic selection as a win-win solution for economic growth and environmental responsibility.
4. Despite its advantages, genomic selection faces barriers to widespread adoption, mainly due to high initial investment costs and the need for specialised infrastructure and expertise. Small and medium-sized producers may find the costs of genomic testing prohibitive, highlighting the need for policy support, financial incentives, and educational programs to facilitate wider implementation.

5. As genomic technologies evolve, future research should focus on enhancing prediction accuracy, reducing costs and developing region-specific breeding strategies. Integrating genomics with precision agriculture and digital livestock management tools offers exciting opportunities to optimise efficiency and profitability in beef production further.
6. Maximising genomic selection's economic potential will require collaboration between researchers, industry stakeholders and policymakers. Supportive policies, investment in genomic infrastructure and knowledge transfer initiatives will ensure that genomic selection becomes integral to future beef breeding strategies.
7. Genomic selection represents a transformative innovation in beef cattle breeding. While challenges remain, its long-term economic advantages, sustainability benefits and potential to enhance market positioning make it a compelling strategy for modern beef production. With continued advancements and industry-wide adoption, genomic selection is set to play a pivotal role in shaping the beef industry's future.

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