




Sustainability in Livestock from the Perspective of Nutrigenomics

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Abstract. Sustainability in livestock refers to conducting production not only from an economic perspective but also in a balanced manner considering environmental, social, and animal welfare dimensions. The aim is to efficiently use natural resources, minimize negative environmental impacts, protect animal health and welfare, secure producers' incomes, and ensure healthy production systems for future generations. Nutrigenomics in livestock is an interdisciplinary approach that examines the effects of nutrition on the genome at a molecular level. This field includes studies aimed at optimizing animals' genetic potential to improve feed efficiency, production performance, and environmental outcomes. Nutrigenomic interventions regulate gene expression through specific nutrients, thereby influencing metabolic pathways and enhancing the quality of milk, meat, and other animal products. They also contribute to selecting disease-resistant animals, reducing antibiotic use, and supporting animal welfare. Genomic analyses identify animals' genetic profiles and detect nutrition-responsive genes (Liang et al., 2020). Transcriptomic and proteomic studies reveal which genes are upregulated or suppressed by specific dietary components, elucidating the molecular mechanisms of metabolism, immunity, and growth (Musa et al., 2023). Metabolomic analyses evaluate the effects of feeds on metabolites produced in animals, helping optimize energy and nutrient utilization (Patil, 2021). The molecular and omics data obtained are used to develop individualized feeding strategies tailored to each animal's genetic potential and metabolic needs, thereby simultaneously improving productivity, immune capacity, and product quality.

This review aims to evaluate nutrigenomic studies that provide both economic and ecological benefits in sustainable livestock practices, offering advantages such as reducing greenhouse gas emissions, optimizing natural resource use, and enhancing food security.

Keywords: Nutrigenomics, livestock, nutrition, genes, sustainability

1 Introduction

Sustainable animal production is defined as a production system that efficiently uses natural resources, reduces environmental impacts, and ensures food security. The livestock sector is a focal point of global discussions due to its dependence on water and soil resources and its contribution to greenhouse gas emissions (FAO, 2020). Therefore, sustainable production approaches, through strategies such as improving feed efficiency, enhancing waste management, and developing animal welfare standards, not only reduce environmental pressure but also support economic efficiency, contributing to the continuity of production (Herrero et al., 2021). Moreover, the reliable production of animal-derived products, which provide high-biological-value proteins and micro-nutrients, is vital for ensuring a balanced and healthy diet for society (Garnett et al., 2015). Consequently, sustainable animal production should be regarded not only as an approach that preserves ecological balance but also as a holistic strategy that supports rural development, ensures food security, and establishes a reliable production system for future generations.

In this context, nutrigenomics, a modern scientific discipline that examines the effects of nutrition on the genome at the molecular level, has gained importance (Malgwi et al., 2022). Sustainability in livestock production refers to managing production in a balanced manner not only economically but also environmentally, socially, and in terms of animal welfare. The goals include efficient use of natural resources, minimizing negative environmental impacts, protecting animal health and welfare, securing producers' incomes, and transferring healthy production systems to future generations. Nutrigenomics contributes to animal production by studying the genetic responses of animals to nutrients, identifying individual differences, and developing targeted feeding strategies. This approach enhances feed utilization efficiency, enabling higher productivity with less feed, thus optimizing resource use and reducing greenhouse gas emissions. Additionally, feeding models tailored to animals' genetic characteristics support immune function, increase disease resistance, and reduce the need for antibiotics and veterinary interventions. Therefore, nutrigenomics emerges as an innovative and scientific tool for achieving sustainable livestock production goals.

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1.1 Sustainability

Nutrigenomic approaches are key tools for developing strategies that support sustainability in livestock production. Understanding the effects of nutrition on genetic responses is critical for environmental sustainability. Particularly, low-emission feeding strategies are being investigated to understand how they influence genes and enzyme pathways involved in methane production. Nutrigenomics thus enhances both animal productivity and climate change mitigation (Bruh et al., 2017). Feed efficiency and resource utilization can be improved by understanding the genetic mechanisms that determine feed utilization, and specialized feed formulations enable higher production

with less feed. For example, methionine and lysine supplementation optimizes the rumen microbiota and increases energy conversion (Malgwi et al., 2022). In terms of environmental impact reduction, excess nitrogen and phosphorus excreted during metabolism cause pollution. Nutrigenomics reveals the metabolic processes at the genetic level, minimizing nitrogen and phosphorus losses; for instance, phytase enzyme supplementation and low-phosphorus diets can reduce manure phosphorus emissions by up to 30% (Kaput & Rodriguez, 2004). For animal health and welfare, determining the nutritional requirements of disease-resistant animals at the genetic level reduces antibiotic use and prevents environmental residues; selenium's activation of glutathione peroxidase, which reduces oxidative stress in dairy cows, exemplifies this (Zhou et al., 2020). Nutrigenomics also improves milk and meat fatty acid profiles, protein content, and micronutrient values, supporting sustainability and reducing waste within the food chain; for example, cows fed omega-3 produce milk with higher levels of conjugated linoleic acid (CLA), beneficial for human health (Gómez-Cortés et al., 2018). Finally, nutrigenomic studies address climate change by investigating genetic and metabolic pathways responsible for methane production, enabling the development of low-methane feeding strategies; tannic acid and fat-based feed additives suppress rumen methanogen gene expression and reduce greenhouse gas emissions (Musa et al., 2023). Nutrigenomic applications enhance both production efficiency and environmental/climatic sustainability. Compared to traditional feeding approaches, nutrigenomics offers more comprehensive analytical capabilities and, unlike transgenic approaches, is more cost-effective and feasible (Bruh et al., 2017). However, integrating and interpreting large datasets from various omics technologies remains challenging, with bioinformatics tools and AI-supported analysis methods playing a crucial role.

1.2 Nutrigenomics

Nutrigenomics investigates the interactions between nutrition and the genome at the molecular level. It examines how nutrients and dietary components affect gene expression, metabolism, protein synthesis, and cellular functions, as well as how genetic differences shape individual responses to nutrients. Key nutrients such as vitamins, minerals, amino acids, and fatty acids are studied using genomic, transcriptomic, proteomic, and metabolomic techniques to understand their influence on intracellular signaling pathways and gene expression, and how single nucleotide polymorphisms (SNPs) contribute to variable responses among individuals. Recent advances in molecular biology, particularly “omics” technologies—transcriptomics, proteomics, metabolomics, and lipidomics—have added a new dimension to animal nutrition research. These technologies allow simultaneous analysis of entire gene sets, protein networks, and metabolite profiles, enabling a comprehensive assessment of gene-diet interactions (Pal, 2022). Unlike nutrigenetics, which primarily studies how genetic variation affects responses to diet, nutrigenomics also investigates how nutrients modulate gene expression (Malgwi et al., 2022). In this context, nutrigenomics has significant potential to improve production efficiency, prevent diseases, and enhance product quality in live-

stock. Broadly, nutrigenomics investigates the mechanisms through which nutrition affects animal health, productivity, and product quality via genes. It focuses on critical production parameters such as feed efficiency, growth performance, milk and meat quality, and immune response (Hasan et al., 2019). Thus, nutrigenomics has a critical role not only for animal health and productivity but also for sustainability.

Through advanced omics approaches—transcriptomics, proteomics, metabolomics, and lipidomics—nutrigenomics enables the identification of biomarkers related to animal health, productivity, and disease resistance. Transcriptomic studies reveal how specific dietary components affect gene expression, while proteomic and metabolomic analyses provide a more holistic understanding of animal biology at the protein and metabolite levels (Hasan et al., 2019; Asmelash, Mahlet & Brhane, 2018). These insights are directly applicable to feed formulation optimization, productivity improvement, and reduced antibiotic use, thereby benefiting both animal welfare and human health (Zhou et al., 2020).

Nutrigenomics regulates metabolic pathways by modulating gene expression in response to specific nutrients, enhancing production performance while mitigating environmental impacts. For example, efficient utilization of energy and nutrients from feed minimizes the excretion of nitrogen and phosphorus into the environment, contributing to sustainable production (Kaput & Rodriguez, 2004).

1.3 Sustainable Livestock Production

In the context of sustainable livestock production, nutrigenomics also contributes to reducing greenhouse gas emissions and combating climate change. Identifying and optimizing genetic and metabolic pathways responsible for methane production minimizes environmental impacts while enhancing production efficiency (Musa et al., 2023). Additionally, nutrigenomic interventions can improve the nutritional quality of animal products, supporting human health and promoting sustainability within the food chain (Gómez-Cortés et al., 2018). Nutrigenomics thus holds considerable potential for sustainable livestock production. Understanding nutrient effects on animal genomes at the molecular level facilitates improved feed efficiency and more effective use of natural resources. Specifically formulated diets can optimize animals' genetically determined metabolic pathways, achieving higher production performance with less feed (Malgwi et al., 2022). Nutrigenomic strategies also reduce unnecessary excretion of nutrients such as nitrogen and phosphorus, lowering environmental burdens and providing a basis for sustainable livestock practices (Kaput & Rodriguez, 2004). Furthermore, selecting disease-resistant animals and understanding nutrient-gene interactions enables reduced antibiotic use, positively impacting both environmental and public health (Zhou et al., 2020). Nutrigenomic interventions enhance the nutritional quality of milk and meat, producing health-promoting components and supporting sustainability within the food chain (Gómez-Cortés et al., 2018). Moreover, examining genetic and metabolic pathways responsible for methane production at the nutrigenomic level contributes to lowering greenhouse gas emissions and combating climate change (Musa et al., 2023). In this framework, nutrigenomics is recognized as a critical tool for developing

balanced and sustainable livestock production practices from both economic and ecological perspectives.

1.4 Nutrigenomics Studies

Nutrigenomic studies in livestock employ various “omics” approaches to understand the molecular effects of nutrients on animal health and productivity. Transcriptomics analyzes gene expression profiles to assess how nutrients influence genetic activity, with microarray and RNA-seq methods revealing how feeds alter gene expression. Initially applied to small ruminants, these methods are now used in cattle to investigate production parameters such as feed efficiency and milk composition (Osorio et al., 2017; Martyniuk et al., 2020). Proteomics focuses on protein identification, quantification, and functional pathway elucidation, with mass spectrometry, two-dimensional gel electrophoresis, and chromatography techniques widely used. Proteomics plays a vital role in understanding reproductive physiology, identifying disease biomarkers, and developing selection strategies (Hasin et al., 2017). Metabolomics examines small molecule metabolites and characterizes biochemical networks, with nuclear magnetic resonance (NMR) and mass spectrometry being commonly employed. This approach identifies biomarkers related to feed efficiency, energy metabolism, and immune response (Hasin et al., 2017). Lipidomics focuses on lipid profiles and metabolic pathways, serving as an important tool for understanding processes such as meat quality, fatty acid composition, and adipogenesis at the molecular level. The effects of vitamins A and D on lipid metabolism are also revealed through lipidomic analyses (Nowacka & Wozuk, 2020). These omics approaches provide the foundation for nutrigenomic research in livestock, enabling a holistic evaluation of nutrient-gene interactions on production, health, and sustainability.

Nutrigenomics has multifaceted applications in livestock. Understanding rumen microbiota responses to feed components is critical for feed efficiency and animal health (Liang et al., 2020). For dairy cows, the transition period from late gestation to early lactation is particularly challenging, with a high likelihood of health problems. Timely post-partum and metabolic adaptation to this new physiological state requires proper management strategies (Butler, 2001; Pascottini et al., 2020).

In animal sciences, nutrigenomics aims to enhance farm animal welfare and commercially important traits through dietary interventions. Increasing evidence indicates that nutrient supplementation can effectively manage metabolic stress in dairy cows during the transition period. Supplements containing polyunsaturated fatty acids, vitamins, dietary amino acids, and phytochemicals regulate energy homeostasis and mitigate metabolic problems. Nutrition strategies, including nutrient supplementation, are among the most studied approaches to manage transition-related stress. Dietary components influence the expression of various genes directly or indirectly involved in stress responses. Nutrigenomics, an interdisciplinary approach combining nutrition science with omics technologies, opens new avenues to study complex interactions between food and the genome. This revolutionary technique highlights the importance of food-gene interactions on diverse physiological and metabolic mechanisms.

Moreover, nutrigenomics provides valuable insights for the meat industry, including meat quality improvement, functional food production, and links to human health. Applications include understanding gene-diet interactions at the molecular level and implementing practical improvements in production processes. Feed costs constitute the largest portion of total production expenses in livestock, and nutrigenomic studies aim to increase feed efficiency by linking animals' feed utilization to their genetic profiles. Transcriptomic and metabolomic analyses reveal molecular indicators of individual feed efficiency by elucidating gene pathways related to energy production, nitrogen metabolism, and growth (Liang et al., 2020). In ruminants, the rumen microbiome plays a central role in nutrient breakdown and energy production; nutrigenomic approaches investigate how feed additives such as probiotics, prebiotics, or plant extracts affect rumen microbial gene expression, contributing to reduced methane emissions, enhanced energy utilization, and prevention of metabolic disorders (Malgwi et al., 2022). Nutrigenomic studies are also used to improve milk and meat quality. Genes and metabolic pathways associated with milk fatty acid composition, protein profile, and biological value have been identified, and omega-3 enriched diets have been shown to enhance functional properties of milk fat (Osorio et al., 2017). Similarly, lipidomic studies reveal biomarkers associated with meat fatty acid profile and marbling, improving meat quality and supporting the production of health-beneficial products (Nowacka & Wozuk, 2020).

Table 1. Nutrigenomics Studies in animal husbandry

| Omics approach | Ap-Objective | Methods | Applications |
|--------------------------|--|---|---|
| Transcriptomics | Analyze gene expression profiles to determine the effects of nutrients on genetic activity | Microarray, RNA-seq | Feed-induced gene expression changes, milk composition, feed efficiency, management of transition period metabolic stress |
| Proteomics | Identify proteins, quantify abundance, and elucidate functional pathways | Mass spectrometry, 2D gel electrophoresis, chromatography | Reproductive physiology analysis, disease biomarker identification, selection strategies |
| Metabolomics | Examine small molecule metabolites and characterize biochemical networks | NMR, mass spectrometry | Feed efficiency, energy metabolism, immune response, prevention of metabolic disorders |
| Lipidomics | Analyze lipid profiles and metabolic pathways | Lipid analysis techniques | Meat and milk quality, fatty acid composition, adipogenesis, study of vitamin A and D effects |
| Rumen microbiome studies | Understand microbial responses and optimize energy/methane conversion | Microbial gene expression analysis | Reduced methane emissions, improved energy utilization, prevention of metabolic disorders |

| Omics approach | Ap-Objective | Methods | Applications |
|------------------------------------|--|---|---|
| Nutrient-gene interactions | Enhance animal health, production, and immune response | Omics data + nutrient supplementation | Omega-3 enriched milk, high CLA content, improved meat fatty acid profile, regulation of immune-related gene expression |
| Integration into genetic selection | Target gene and improved utilization | Genotype \times diet interactions, omics data | Optimized feed efficiency, milk and meat quality, disease tolerance, overall production efficiency |

Immune responses to nutrition are also examined at the molecular level; vitamins (A, D, E) and trace minerals (zinc, selenium) regulate gene expression related to immunity, exhibiting anti-inflammatory and immunomodulatory effects (Hasin et al., 2017). Finally, nutrigenomic data can be integrated into genetic selection programs, enabling targeted selection of genes, enhanced feed efficiency, and improved disease tolerance. Genetic markers and genotype \times diet interactions, supported by omics data, make breeding programs more precise and efficient, with selection criteria based on feed efficiency, milk composition, immunity, and meat quality (Martyniuk et al., 2020). Thus, production efficiency, animal health, and nutrient utilization are optimized simultaneously.

2 Conclusion

From a sustainable livestock perspective, nutrigenomic studies provide significant gains in productivity and health by focusing on interactions between animal nutrition and genetics. These studies allow animals to utilize feed resources more efficiently and minimize disease risks. Environmental impacts can be reduced, and natural resources can be used more efficiently. Consequently, nutrigenomic approaches emerge as important tools for sustainable livestock production, both economically and environmentally, and are poised to become strategic components of future genetic breeding programs.

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