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Nutrigenomic Intelligence: Decoding the Molecular Dialogue between Feed and Genes

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Abstract:

The advance of nutrigenomics has revolutionized animal nutrition by molecular interactions between dietary compounds and the genome. Nutrients are recognized not only as substrates for growth and production but also as regulatory molecules for gene expression through transcriptional, post-transcriptional and epigenetic mechanisms. These nutrient–gene interactions influence a variety of biological processes including energy metabolism, immune competence, reproductive efficiency, tissue development, stress adaptation and product quality. Recent advances in genomics, transcriptomics, and systems biology have enabled the identification of gene which regulated by diet and molecular pathways that economically important for livestock. The integration of nutrigenomics with precision livestock nutrition and multi-omics technologies provides opportunities for the development of feeding strategies based on genetic and physiological profiles of individual animal. Consequently, nutrigenomic approaches which enhance feed efficiency, milk and meat quality, disease prevention, mitigate metabolic disorders and reduce the environmental issues. This article highlights its potential to provide sustainable, efficient livestock production information in the era of precision agriculture.

Keywords: Nutrigenomics, gene expression, livestock, precision nutrition, molecular science

Introduction:

Traditional animal nutrition mainly focuses on supplying of nutrients for maintenance, growth, production and reproduction. However, in recent molecular science with advancement in animal biotechnology, which gives more ideas about how the feed do proper functional in animal body. Essential nutrients and their bioactive compounds in feed, which interact with a particular gene for their functionality and affect physiological function, animal health and productivity. This emerging science is

called nutrigenomics which is how dietary nutrients or it active compounds affect gene expression, lead to genetic effects on animals. Recently, nutrigenomics has gained focus due to extensive research in livestock applications. Feed is not solely a source of nutrients; which serve as powerful biological signal capable of regulating metabolic pathways and cellular functions (Chandaka et al., 2024). Knowledge of nutrigenomics has opened new opportunities to improve productivity, feed efficiency, disease resistance, product quality and environmental sustainability in livestock production systems. This article provides an overview of fundamental concept, molecular mechanisms, major applications and future prospects of nutrigenomics.

Concept of Nutrigenomics:

Nutrigenomics is obtained from the two words "nutrition" and "genomics." It is interactions between nutrients and the genome, particularly how dietary factors influence gene expression, protein synthesis and metabolic processes (Kore et al., 2008). It is different from genetic modification which alter the DNA sequences while nutrigenomics affects how genes are activated or suppressed under different nutritional conditions in body. Genes contain proper instruction which required for various biological processes. However, not all genes are active at the same time and environmental factors, including nutrition, determine which genes are active or supress (Nowacka-Woszuk, 2019).

Mechanisms of Action:

- **Regulation through Transcription Factors**:

  Transcription factors are protein molecules which bind to specific DNA sequences and regulate the activity of genes. Certain nutrients directly interact with transcription factors that control gene activity. For example, the gene Peroxisome Proliferator-Activated Receptors (PPARs) which regulate the lipid metabolism and energy utilization of fatty acids and the Sterol Regulatory Element-Binding Protein 1 (SREBP-1) gene play an important role in responsible for fatty acid and cholesterol synthesis (Guo et al., 2024).

- **Cell Signalling Pathways:**

  Certain nutrients activate intercellular pathways that transfer information from cell surface to the nucleus. These pathways are associated with cellular nutritional responses. For example, leucine amino acids which activate the mammalian target of rapamycin (mTOR) pathway which regulate the protein synthesis, cellular growth, and tissue development. Another important pathway is the AMP-activated protein kinase (AMPK) pathway. AMP-activated protein kinase (AMPK) pathway responds to cellular energy status and regulate genes involved in glucose metabolism and energy homeostasis (Haq et al., 2022).

- **Epigenetic Regulation:**

  Those Nutrients can alter gene expression without changing the DNA sequence, mainly through DNA methylation and Histone modification are called Epigenetic regulation. Nutrients like

folate, choline, methionine, and vitamin B12 act as methyl donors and undergo DNA methylation while histone modification alter the structure of chromatin. These changes are long-lasting throughout life and affect animal growth and productivity (Iqbal & Usman, 2025).

- **Interaction with microRNAs:**

Nutrients can interact with microRNAs and other non-coding RNAs and regulate gene expression in animals. MicroRNAs are small molecules of RNA that do not encode proteins but regulate the inhibition of mRNA translation and enhancing mRNA degradation. Recent research in biotechnology suggested that bioactive compounds interact with microRNAs and affect the various biological processes including immune function, lipid metabolism and muscle development (Haq et al., 2022).

Applications of Nutrigenomics:

Recent advances in nutrigenomics have identified several genes and molecular pathways which can modulated through nutrition to improve animal performance (Osorio & Moisa, 2019; Souf et al., 2026). The key applications of nutrigenomics in livestock and their practical significance are summarized in Table 1.

Table 1. Applications of nutrigenomics in livestock, representative genes and their practical significance

S. No.	Application of Nutrigenomics	Representative Genes	Practical Significance
1	**Improving milk composition**	SCD1, FASN, ACACA, SREBF1, CSN2, CSN3, STAT5A, mTOR	Improves milk yield, milk fat percentage, protein content and nutritional quality of milk
2	**Enhancing feed efficiency**	IGF1, LEP, GHR, PPARGC1A, PPARA	Better feed conversion ratio, reduced feed cost and improved production efficiency
3	**Supporting growth and muscle development**	MSTN, IGF1, MYOD1, MYOG	Increased growth rate, lean muscle deposition and improved body weight gain
4	**Improving fertility and reproduction**	FSHR, LHR, ESR1, CYP19A1	Enhanced conception rate, fertility, embryo survival and reproductive efficiency
5	**Strengthening immunity**	TLR4, IL6, TNF-α, IFNG	Increased disease resistance and improved immune competence
6	**Reducing metabolic disorders**	PPARG, AMPK, SIRT1, PPARA	Reduced incidence of ketosis, fatty liver and metabolic stress in high-producing animals
7	**Improving meat quality**	PPARG, FABP4, SCD1, FASN	Improved tenderness, marbling, flavour and carcass value
8	**Manipulating gut health and microbiome**	MUC2, SLC5A1, CLDN1, OCLN	Better gut health, nutrient digestibility and microbial balance
9	**Reducing methane emissions**	MCT1 (SLC16A1), PPARA, ACSS2, CPT1A	Lower methane production and improved environmental sustainability
10	**Enhancing stress tolerance**	HSP70 (HSPA1A), HSP90AA1, SOD1, CAT	Improved heat tolerance and resilience to environmental challenges
11	**Improving antioxidant defence**	GPX1, SOD1, CAT, NFE2L2 (NRF2)	Enhanced cellular protection, health and productivity
12	**Early-life nutritional programming**	IGF2, DNMT1, DNMT3A, H19	Improved growth, health and productivity throughout life
13	**Improving product quality (milk, meat, eggs)**	SREBF1, PPARG, FASN, STAT5A	Production of higher-quality animal products with greater consumer value

Future Prospects:

The future of nutrigenomics which is closely associated with bio genomics, bioinformatics, artificial intelligence and precision livestock nutrition. Future development is needed in following includes

- Precision nutrition strategies for individual animals.
- Integration of knowledge of genomics with feeding management.
- Development of nutrigenomic biomarkers for the health and productivity of animals.
- Identification and selection of the best genes for future breeding.
- Improved disease prevention through dietary management.
- Targeted nutritional interventions for reduced greenhouse gas emissions.
- Use of multi-omics technologies including transcriptomics, proteomics, metabolomics, and microbiomics with nutrigenomics.

Conclusion:

Nutrigenomics represents a significant development in animal nutrition science by demonstrating that feed is not only sources of nutrients but also acts as a regulator of gene expression. Nutrition can influence metabolism, immunity, growth, reproduction and production through act at the molecular level via transcription factors, signalling pathways and epigenetic mechanisms. As the new technologies become affordable and accessible, nutrigenomics acts as an integral part of sustainable livestock development and animal production.

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