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Functional Biomolecules in Animal Nutrition: Biochemical Mechanisms and Their Impacts on Growth Performance and Health Outcomes

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Abstract

Functional biomolecules have emerged as critical modulators of animal nutrition, extending beyond conventional nutrient supply to regulate biochemical and physiological processes that determine growth performance and health outcomes. This review synthesizes current knowledge on diverse classes of bioactive compounds, including amino acids, peptides, fatty acids, vitamins, minerals, phytochemicals, and microbial-derived metabolites, and their roles in livestock systems. Emphasis is placed on underlying biochemical mechanisms such as enzyme activation, nutrient signaling pathways, gene expression modulation, and antioxidant defense systems. These biomolecules influence key metabolic pathways involved in protein synthesis, energy utilization, lipid metabolism, and immune function. Recent advances highlight the interaction between functional biomolecules and the gut microbiome, where microbial fermentation products and host microbe crosstalk contribute to improved nutrient digestibility, intestinal integrity, and disease resistance. Evidence demonstrates that strategic inclusion of functional biomolecules enhances feed efficiency, promotes muscle growth, supports reproductive performance, and mitigates metabolic and oxidative stress-related disorders. In addition, these compounds serve as effective alternatives to antibiotic growth promoters, aligning with global efforts toward sustainable and responsible livestock production. The integration of omics technologies, including metabolomics and proteomics, has further advanced the understanding of biomolecule-driven nutritional regulation, enabling precision feeding strategies tailored to species, production stage, and environmental conditions. However, challenges remain regarding bioavailability, dosage optimization, variability in responses, and economic feasibility. Future research should focus on mechanistic validation, the development of cost-effective delivery systems, and field-level applications. Overall, functional biomolecules represent a promising avenue for enhancing livestock productivity, health, and sustainability through targeted nutritional biochemistry.

Keywords: Animal health, bioactive compounds, feed efficiency, growth performance, metabolomics, nutritional biochemistry

INTRODUCTION

Animal nutrition has evolved from a focus on meeting basic dietary requirements to a more refined understanding of how specific biomolecules influence physiological and biochemical functions in livestock. Traditionally, nutrients – such as proteins, carbohydrates, lipids, vitamins, and minerals – were primarily evaluated based on their role in maintenance and production. However, recent advances in Nutritional Biochemistry have revealed that many of these components, along with additional bioactive compounds, act as functional biomolecules that regulate metabolic pathways, cellular signaling, and gene expression [1–4]. This shift has opened new opportunities to enhance growth performance and health outcomes through targeted nutritional strategies [5–7].

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Functional biomolecules, including amino acids, peptides, fatty acids, phytochemicals, and microbial metabolites, exert their effects through diverse biochemical mechanisms. These include modulation of enzyme activity, participation in redox balance, and interaction with signaling pathways that control protein synthesis, energy metabolism, and immune responses [8–11]. The integration of these biomolecules within physiological systems highlights the complexity of nutrient utilization beyond simple digestion and absorption. Furthermore, the interaction between dietary biomolecules and the Gut Microbiome has gained increasing attention, as it plays a central role in fermentation, nutrient transformation, and the production of metabolites that directly influence host health and productivity [12–14].

Despite substantial progress, important gaps remain in understanding the context-specific effects of functional biomolecules across species, production stages, and environmental conditions. Current research often relies on controlled experimental settings, with limited validation under field conditions and in diverse production systems. In addition, there is insufficient integration of multi-omics approaches, particularly Metabolomics and Proteomics, to establish causal relationships between biomolecular interventions and phenotypic outcomes. Variability in bioavailability, dose response, and interactions among biomolecules further complicate their practical application. This study addresses these limitations by adopting an integrative framework that combines biochemical mechanisms with systems-level analysis to evaluate the role of functional biomolecules in livestock nutrition. The novelty lies in linking molecular insights with practical performance indicators, thereby providing a more comprehensive and translational perspective for improving growth efficiency and health outcomes in sustainable livestock systems.

BIOACTIVE MOLECULES

Proteins, Peptides, and Amino Acid Derivatives

Proteins and peptides serve not only as structural and functional components but also as regulators of metabolic processes in animals. Bioactive peptides can influence hormone secretion, immune responses, and enzyme activity, while specific amino acid derivatives – such as glutamine and arginine – support gut integrity and immune function. These biomolecules are directly involved in protein synthesis, nitrogen balance, and cellular signaling pathways. Their targeted supplementation can improve growth performance, tissue development, and recovery from physiological stress in livestock systems [15–17].

Lipids and Fatty Acid-Based Biomolecules

Lipids, particularly functional fatty acids, play critical roles in energy metabolism, membrane integrity, and signaling processes. Polyunsaturated fatty acids – such as omega-3 and omega-6 – regulate inflammatory responses, gene expression, and lipid metabolism. Certain lipid-derived molecules act as signaling mediators that influence metabolic efficiency and immune modulation. Additionally, lipids improve the energy density of diets and enhance the absorption of fat-soluble vitamins. Strategic inclusion of functional lipids contributes to improved growth, reproductive efficiency, and overall health in animals [18–20].

Carbohydrate-Derived Bioactives

Carbohydrates extend beyond energy provision by generating bioactive compounds such as oligosaccharides and resistant starches. These components act as prebiotics, selectively stimulating beneficial gut microbes and enhancing fermentation processes. Short-chain fatty acids produced during microbial fermentation serve as energy sources and regulators of intestinal health. Carbohydrate-derived biomolecules also influence glycaemic control and metabolic signaling pathways. Their inclusion in diets supports gut health, nutrient digestibility, and improved feed efficiency in livestock production systems [21–23].

Vitamins, Minerals, and Cofactors

Vitamins and minerals function as essential cofactors in numerous biochemical reactions, supporting enzyme activity, antioxidant defense, and metabolic regulation. They are critical for processes such as energy production, bone development, and immune function. Trace minerals – like zinc and selenium – play roles in redox balance and cellular protection, while vitamins – such as A, D, and E – regulate gene expression and physiological functions. Adequate and balanced supply of these micronutrients ensures optimal growth, health maintenance, and resilience against stress and disease [24–26].

Phytochemicals and Plant Secondary Metabolites

Phytochemicals, including flavonoids, tannins, and essential oils, are plant-derived compounds with significant bioactive properties. These biomolecules exhibit antioxidant, antimicrobial, and anti-inflammatory effects, contributing to improved gut health and immune response. They can modulate rumen fermentation, reduce methane production, and enhance nutrient utilization. Phytochemicals also serve as natural alternatives to synthetic additives and antibiotics. Their application in animal nutrition supports sustainable production while improving growth performance and disease resistance [16, 27, 28].

Microbial-Derived Biomolecules such as Probiotics and Postbiotics

Microbial-derived biomolecules include probiotics, prebiotics, and postbiotics that influence the gut ecosystem and host metabolism. Probiotics are live beneficial microbes that enhance microbial balance and inhibit pathogens, while postbiotics are metabolic products – such as enzymes, peptides, and organic acids – that exert functional effects. These biomolecules improve nutrient digestion, strengthen intestinal barrier function, and modulate immune responses. Their inclusion in animal diets promotes gut health, enhances feed efficiency, and reduces reliance on antibiotic growth promoters [1, 10, 16].

MODE OF ACTIONS

Role in Enzyme Activation and Metabolic Pathways

Functional biomolecules act as activators, inhibitors, or cofactors of enzymes that drive core metabolic pathways. Vitamins and minerals support catalytic activity, while specific amino acids and peptides modulate enzyme synthesis and turnover (Figure 1). These interactions regulate pathways involved in glycolysis, protein synthesis, lipid metabolism, and energy production. By optimizing enzymatic efficiency, biomolecules enhance nutrient digestion, absorption, and conversion into productive outputs, such as muscle growth and milk synthesis, thereby improving overall metabolic efficiency in livestock [1, 2, 9]

Nutrient Signaling and Gene Expression Regulation

Many functional biomolecules serve as signaling molecules that influence cellular communication and gene expression. Through pathways studied in Nutrigenomics, nutrients can activate transcription factors and regulate genes associated with growth, metabolism, and immunity. Fatty acids, amino acids, and vitamins can modulate hormonal responses and intracellular signaling cascades. This regulation ensures that metabolic processes are aligned with dietary inputs, enabling animals to adapt efficiently to varying nutritional conditions and improving productivity and physiological balance [1, 2, 16].

Interaction with Gut Microbiota and Fermentation Processes

Functional biomolecules closely interact with the Gut Microbiota, influencing microbial composition and activity. Prebiotics and certain fibers promote beneficial microbes, while microbial fermentation produces metabolites – such as short-chain fatty acids – that support intestinal health and energy supply. These interactions enhance nutrient breakdown, improve digestibility, and contribute to the synthesis of essential biomolecules. The symbiotic relationship between diet and microbiota plays a crucial role in maintaining gut integrity, immune function, and overall animal performance [11, 16, 19, 23].

Antioxidant and Anti-Inflammatory Mechanisms

Functional biomolecules contribute to maintaining cellular homeostasis by regulating oxidative and inflammatory processes. Antioxidants – such as vitamins, minerals, and phytochemicals – neutralize reactive oxygen species, preventing cellular damage and improving metabolic stability. Anti-inflammatory compounds modulate immune signaling pathways, reducing chronic inflammation and associated metabolic disorders. These mechanisms are particularly important under stress conditions, such as heat or disease challenge, where oxidative imbalance can impair productivity. Effective antioxidant and anti-inflammatory responses support resilience, health, and sustained growth in livestock systems [11, 16, 19].

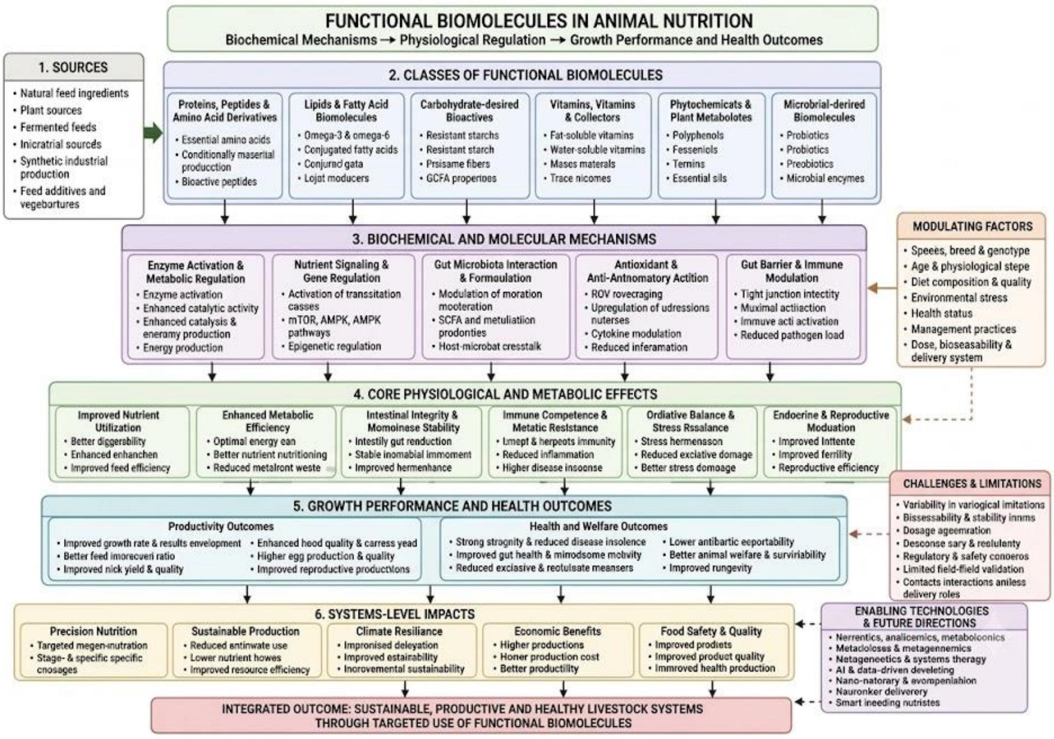

Figure 1. Integrated conceptual framework illustrating functional biomolecules, biochemical mechanisms, gut microbiome interactions, and their effects on growth performance, health outcomes, and sustainable livestock production.

ROLE IN GROWTH AND PRODUCTIVITY

Effects on Feed Efficiency and Nutrient Utilization

Functional biomolecules improve feed efficiency by enhancing the digestion, absorption, and metabolic conversion of nutrients. Enzymes, amino acids, and bioactive compounds increase the availability of energy and essential substrates from feed, reducing nutrient wastage. Improved synchronization between nutrient supply and metabolic demand leads to better feed conversion ratios [20, 25]. These effects support more efficient livestock production systems by lowering feed costs while maximizing output, particularly in intensive production environments where nutrient optimization is critical for economic sustainability (Tables 1 & 2) [1, 11, 20].

Muscle Growth, Protein Synthesis, and Tissue Development

Functional biomolecules play a central role in regulating protein synthesis and tissue accretion. Amino acids – such as leucine, lysine, and methionine – stimulate muscle protein synthesis through activation of anabolic signaling pathways. Peptides and growth-related biomolecules enhance cellular proliferation and tissue repair [20, 25]. These processes are essential for skeletal muscle development, organ growth, and overall body composition. Enhanced protein turnover efficiency leads to improved weight gain and carcass quality, making these biomolecules vital for meat-producing livestock systems [1, 11, 20].

Table 1. Integrated functional biomolecules, molecular targets, and physiological consequences in livestock systems.

Functional biomolecule class	Representative compounds	Primary molecular targets	Core biochemical mechanisms	Major metabolic pathways affected	Gut microbiome interaction	Physiological outcomes	Production and health impacts
Carbohydrate-derived bioactives	Oligosaccharides, resistant starch, and prebiotic fibers	Gut microbiota, intestinal receptors, fermentative microbes	Fermentation enhancement, SCFA generation, nutrient signaling	Glycolysis, fermentation metabolism, glucose regulation	Promotes beneficial microbiota and suppresses pathogens	Improved nutrient digestibility and barrier integrity	Enhanced feed efficiency and intestinal health.
Lipids and fatty acid biomolecules	Omega-3, omega-6, phospholipids, conjugated fatty acids	Cell membranes, transcription factors, and inflammatory mediators	Lipid signaling, membrane stabilization, and inflammatory modulation	Lipid metabolism, energy metabolism, and endocrine regulation	Alters microbial fermentation and SCFA production	Reduced inflammation, improved metabolic flexibility	Better reproductive performance, improved milk and meat quality.
Microbial-derived biomolecules	Probiotics, postbiotics, organic acids, microbial enzymes	Gut microbiota, epithelial cells, and immune receptors	Competitive exclusion, metabolite production, and immune modulation	Fermentation pathways, intestinal metabolism, and immune pathways	Direct modulation of microbial ecology	Enhanced gut stability and nutrient utilization	Better feed conversion and disease resistance.
Phytochemicals and plant metabolites	Flavonoids, tannins, polyphenols, and essential oils	Reactive oxygen species, inflammatory mediators, and rumen microbes	Antioxidant activity, antimicrobial action, and anti-inflammatory regulation	Redox metabolism, immune signaling, rumen fermentation	Modulates microbial diversity and fermentation efficiency	Reduced oxidative stress and pathogen load	Lower antibiotic dependence and improved health status.
Proteins, peptides, and amino acid derivatives	Glutamine, arginine, leucine, lysine, methionine, bioactive peptides	mTOR, ribosomes, immune cells, intestinal epithelium	Protein synthesis activation, nitrogen metabolism, cellular signaling	Protein accretion, amino acid metabolism, and immune metabolism	Supports intestinal epithelial repair and microbial balance	Improved muscle development, enhanced immunity, better gut integrity	Higher growth rate, improved carcass quality, and disease resistance.
Vitamins, minerals, and cofactors	Vitamins A, D, E, Zn, Se, Fe	Enzymes, antioxidant systems, transcription factors	Cofactor activation, antioxidant defense, metabolic regulation	Oxidative phosphorylation, antioxidant pathways, and immune pathways	Supports microbial stability indirectly through immune competence	Reduced oxidative damage and metabolic stress	Improved resilience, productivity, and survivability.

Milk, Meat, and Egg Production Responses

Functional biomolecules significantly influence production traits across livestock species. In dairy animals, they enhance milk yield and improve fat and protein content by optimizing metabolic energy partitioning [20, 25]. In poultry, they support egg production, shell quality, and yolk composition. In meat-producing animals, they improve carcass yield and meat quality attributes such as tenderness and marbling. These responses are driven by improved nutrient utilization, hormonal regulation, and metabolic efficiency, leading to higher productivity and better product quality [1, 11, 20].

Reproductive Performance and Endocrine Modulation

Reproductive efficiency is closely linked to metabolic and endocrine balance, which is influenced by functional biomolecules. Vitamins, minerals, and fatty acids regulate hormone synthesis, ovarian function, and sperm quality [20, 25]. Bioactive compounds modulate endocrine signaling pathways, improving fertility, estrus expression, and embryo development. Adequate nutrient signaling ensures optimal secretion of reproductive hormones such as estrogen, progesterone, and testosterone. These effects contribute to improved conception rates, reduced reproductive disorders, and enhanced lifetime productivity in livestock systems [1, 11, 20].

Table 2. Systems-level integration of functional biomolecules with precision nutrition, sustainability, and future livestock production.

Systems component	Functional role of biomolecules	Integrated biochemical and physiological mechanisms	Omics and technological integration	Major livestock outcomes	Sustainability implications	Key challenges and research gaps
Future smart feeding systems	Deliver targeted biomolecules with precision	Controlled release, encapsulation, personalized nutrition	Nano-encapsulation, AI modeling, precision sensors	Consistent physiological responses	Resource-efficient livestock production	High technological and implementation costs.
Gut microbiome engineering	Manipulate microbial ecology for improved digestion and health	Host-microbe crosstalk, fermentation, SCFA production	Microbiome profiling, metagenomics, postbiotic discovery	Improved gut integrity and immune competence	Reduced antibiotic use and improved animal welfare	Instability of microbial responses across environments.
Immune and disease management	Enhance innate and adaptive immunity	Cytokine modulation, immune cell activation, intestinal barrier protection	Immuno-metabolomics and microbial diagnostics	Reduced morbidity and mortality	Safer food production with lower antimicrobial resistance risk	Limited field-level validation.
Precision nutrition	Align nutrient supply with metabolic demand	Nutrient sensing, metabolic programming, endocrine regulation	Nutrigenomics, metabolomics, AI-driven feeding models	Optimized growth efficiency and reduced nutrient wastage	Lower feed cost and improved production efficiency	Individual variability and dosage optimization.
Productivity enhancement	Improve nutrient conversion into productive outputs	Enhanced ATP generation, protein accretion, metabolic efficiency	Biomarker-guided supplementation and precision formulation	Increased milk, meat, and egg production	Sustainable intensification of livestock systems	Economic feasibility at commercial scale.
Stress resilience and oxidative balance	Protect against heat, inflammatory, and metabolic stress	ROS scavenging, antioxidant defense, anti-inflammatory signaling	Proteomics, oxidative biomarkers, nano-delivery systems	Improved resilience under environmental stress	Climate-adaptive livestock production	Bioavailability and compound stability.
Sustainable livestock systems	Reduce environmental burden while maintaining productivity	Improved nutrient utilization and methane mitigation	Environmental monitoring and systems biology integration	Efficient and resilient production systems	Reduced greenhouse gas emissions and nutrient losses	Regulatory and scalability limitations.

SOURCES AND DIETARY INCLUSION

Natural Feed Ingredients and Plant Sources

Natural feed ingredients remain the primary source of functional biomolecules in livestock nutrition. Forages, grains, legumes, and oilseed meals provide proteins, fatty acids, vitamins, and mineral cofactors essential for metabolic regulation. Plant-derived compounds – such as polyphenols, flavonoids, and essential oils – also contribute bioactive properties that support immunity and gut health. These ingredients are widely available and cost-effective, making them suitable for sustainable feeding systems, particularly in ruminant-based production, where forage quality strongly influences animal performance [20, 22, 23].

Synthetic and Industrially Derived Biomolecules

Synthetic and industrial sources provide highly purified and standardized functional biomolecules for precise nutritional applications. These include industrially produced amino acids, vitamins, and enzyme preparations generated through microbial fermentation and chemical synthesis. Such biomolecules ensure consistent quality, stability, and targeted functionality in diets. They are particularly useful in intensive livestock systems where specific nutrient deficiencies must be corrected. Industrial production allows large-scale availability and supports the formulation of scientifically balanced rations tailored to production goals [20, 22, 23].

Feed Additives and Supplements

Feed additives and supplements are concentrated sources of functional biomolecules designed to enhance productivity and health. These include enzymes, probiotics, organic acids, antioxidants, and phytogenic compounds incorporated into diets at low inclusion levels. They improve nutrient digestibility, modulate gut microbiota, and enhance metabolic efficiency. Supplementation strategies are often used to address specific physiological needs such as growth promotion, stress reduction, or immune support. Their strategic use contributes to improved feed efficiency and overall livestock performance [18, 21, 22].

Dosage, Bioavailability, and Delivery Systems

The effectiveness of functional biomolecules depends strongly on appropriate dosage, bioavailability, and delivery methods. Optimal inclusion levels must be determined to avoid under or over-supplementation, ensuring maximum biological response. Bioavailability is influenced by the feed matrix, digestion, and interaction with other nutrients. Advanced delivery systems – such as encapsulation, nano carriers, and coated formulations – improve stability and targeted release in the gastrointestinal tract. These innovations enhance absorption efficiency and ensure consistent physiological effects in livestock nutrition [18, 21, 22].

ROLE IN ANIMAL HEALTH AND WELFARE

Immune Modulation and Disease Resistance

Functional biomolecules strengthen the immune system by regulating both innate and adaptive immune responses. Amino acids, vitamins, and bioactive peptides support the production and activity of immune cells such as macrophages, lymphocytes, and neutrophils. These compounds enhance cytokine signaling and antibody production, improving the animal’s ability to resist bacterial, viral, and parasitic infections. Improved immune readiness reduces morbidity and mortality, particularly under intensive production conditions where disease pressure is high, and stress is common [9, 12, 26].

Alternatives to Antibiotic Growth Promoters

Functional biomolecules are increasingly recognized as sustainable alternatives to antibiotic growth promoters in livestock production. Probiotics, prebiotics, and phytochemicals help suppress pathogenic bacteria while promoting beneficial microbial populations. These compounds enhance immunity, gut health, and nutrient utilization without contributing to antimicrobial resistance. Their use aligns with global efforts to reduce antibiotic dependence in animal agriculture. As a result, they support safer food production systems while maintaining growth performance and health efficiency in livestock [18, 19, 22, 24].

Gut Health, Barrier Function, and Microbiome Stability

The intestinal tract is a primary site where functional biomolecules exert protective effects. They enhance the integrity of epithelial tight junctions, reducing pathogen translocation and improving barrier function. Prebiotic compounds and microbial metabolites support a balanced Gut Microbiome by promoting beneficial bacteria and suppressing harmful species. Stable microbial communities improve fermentation efficiency, nutrient absorption, and gut immunity. This integrated effect contributes to better digestive health and overall physiological stability in livestock [18, 19, 22, 24].

Oxidative Stress Management

Oxidative stress occurs when the production of reactive oxygen species exceeds the capacity of antioxidant defense systems, leading to cellular damage. Functional biomolecules – such as vitamins E and C, selenium, and plant-derived antioxidants – help neutralize free radicals and maintain redox balance. These compounds protect lipids, proteins, and DNA from oxidative damage. Proper management of oxidative stress is essential for preventing metabolic disorders, such as fatty liver, ketosis, and inflammatory conditions, which can significantly reduce productivity and overall animal health [9, 12, 26].

Reduce Antibiotic Dependence

Nutritional strategies are increasingly used to reduce reliance on antibiotics in livestock production. Functional biomolecules – such as probiotics, prebiotics, organic acids, and phytochemicals – enhance gut microbial balance and inhibit pathogenic organisms. These interventions improve gut integrity, immune competence, and nutrient absorption without contributing to antimicrobial resistance. By supporting natural defense mechanisms, they maintain animal health and productivity in a sustainable manner. This approach aligns with global efforts to minimize antibiotic use while ensuring safe and efficient livestock production systems [18, 19, 22, 24].

CHALLENGES AND LIMITATIONS

Variability in Responses and Biological Complexity

One of the major challenges in using functional biomolecules is the high variability in biological responses among animals. Differences in species, breed, age, health status, and gut microbial composition can lead to inconsistent outcomes even under similar dietary conditions. The complexity of metabolic networks and nutrient interactions further complicates the prediction of responses. Environmental factors – such as temperature, stress, and management practices – also influence effectiveness. This biological complexity limits the ability to develop universally applicable nutritional strategies based on functional biomolecules [1, 6, 7, 27].

Cost Effectiveness and Scalability

Economic considerations often constrain the commercial application of functional biomolecules. Many bioactive compounds, particularly purified enzymes, amino acids, and specialized additives, are expensive to produce and incorporate into feeds. Large-scale adoption requires cost-effective production technologies and efficient supply chains. In addition, benefits must be clearly measurable in terms of improved productivity or reduced feed cost to justify investment. Scalability remains a key issue, especially in developing regions where livestock producers operate under limited financial resources [1, 6, 7, 20].

Stability, Storage, and Regulatory Concerns

The stability of functional biomolecules during feed processing, storage, and digestion is a significant limitation. High temperatures, moisture, and pH variations can reduce their biological activity, thereby reducing efficacy. Encapsulation and protective formulations are being explored, but they add to production costs. Regulatory approval processes for new biomolecules and feed additives can also be complex and time-consuming, varying across countries. Concerns related to safety, residue levels, and environmental impact further influence their adoption in livestock nutrition systems [1, 6, 7, 28].

FUTURE PERSPECTIVES

Precision Nutrition and Biomolecule-Based Feeding Strategies

Future livestock production will increasingly rely on precision nutrition approaches that utilize functional biomolecules for targeted physiological outcomes. Instead of general diet formulations, feeding strategies will be customized based on production stage, health status, and metabolic needs of individual animals or groups. Advanced biomolecule profiling will allow precise supplementation of amino acids, enzymes, and bioactive compounds to optimize growth, immunity, and reproduction. This shift will improve feed efficiency, reduce waste, and enhance productivity through more accurate alignment of nutrient supply with biological demand.

Integration with Genomics and Microbiome Research

Emerging research is focusing on integrating nutritional science with genomic and microbial data to develop a holistic understanding of animal metabolism. Advances in Genomics enable the identification of genetic traits that influence nutrient utilization and metabolic efficiency. At the same time, studies on the Gut Microbiome reveal its central role in digestion, immunity, and metabolic regulation. Combining these fields with biomolecule-based nutrition will support the development of predictive models for growth performance, disease resistance, and feed response.

Climate-Resilient and Sustainable Livestock Systems

Functional biomolecules are expected to play a key role in developing climate-resilient livestock systems. Heat stress, feed scarcity, and environmental fluctuations significantly affect productivity, and targeted biomolecules can help animals adapt to these challenges. Nutritional strategies that enhance antioxidant capacity, metabolic flexibility, and immune resilience will be essential for maintaining performance under stress conditions. In addition, biomolecule-based feeding can reduce greenhouse gas emissions and nutrient losses, contributing to more sustainable and environmentally friendly livestock production systems in the future.

CONCLUSION

Functional biomolecules represent a major advancement in animal nutrition by extending the role of feed components beyond basic nutrient supply to active regulators of metabolism, immunity, and productivity. Their diverse biochemical functions, including enzyme modulation, nutrient signaling, antioxidant defense, and interaction with the gut microbiome, collectively contribute to improved growth performance and health outcomes in livestock. Evidence across species shows consistent benefits in feed efficiency, tissue development, reproductive performance, and resistance to disease when these compounds are appropriately integrated into diets. The application of functional biomolecules also supports a transition toward reduced reliance on antibiotics and improved sustainability in livestock production. By enhancing nutrient utilization and minimizing metabolic disorders, they contribute to healthier animals and more efficient production systems. However, variability in biological responses, challenges in bioavailability, and economic constraints still limit their full-scale adoption in practical feeding programs. Recent progress in nutritional biochemistry, coupled with advances in omics technologies and precision feeding approaches, is strengthening the scientific foundation for their use. Integration with genomics, microbiome research, and data driven modeling is expected to further refine their application in the future. Overall, functional biomolecules offer a promising pathway for achieving sustainable, productive, and health-oriented livestock systems through targeted nutritional interventions.

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