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Recombinant Proteins and Nested Gene Regulation: Nutrient-Driven Immune Response and Disease Resistance in Livestock

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Abstract

Livestock production systems are increasingly challenged by infectious diseases, metabolic disorders, and environmental stressors that reduce productivity and compromise animal health. Advances in molecular biology and animal nutrition now offer new opportunities to strengthen disease resistance through integrated strategies that combine recombinant protein technologies, gene regulatory mechanisms, and nutrient mediated immune modulation. This review examines how recombinant proteins and nested gene regulation interact to shape nutrient driven immune responses in livestock. Recombinant proteins, including immunomodulatory peptides, cytokines, and functional enzymes, serve as precise biological tools to enhance host defense and regulate immune function. Their use in livestock systems enables targeted interventions that can improve pathogen resistance and reduce reliance on conventional antibiotics. In parallel, nested gene regulation represents a hierarchical genomic system in which genes embedded within larger structures enable fine-tuned control of immune responses under varying physiological conditions. These gene networks allow adaptive and context specific regulation of immunity. Animal nutrition plays a central role in modulating both recombinant protein activity and gene expression pathways. Amino acids, vitamins, minerals, and bioactive feed components influence immune signaling, cytokine production, and metabolic balance. Nutrient sensing pathways interact closely with gene regulatory networks, shaping immune competence and disease resilience. The integration of these mechanisms demonstrates a dynamic interplay between diet, molecular regulation, and immune function. Although challenges remain in scalability, regulatory complexity, and field level application, this integrated framework provides a promising pathway for developing sustainable, disease resistant livestock systems with improved health and productivity.

Keywords: Animal nutrition, disease resistance, immune response, nested gene regulation, recombinant proteins, nutrient immunomodulation

INTRODUCTION

Livestock production systems are a fundamental component of global food security, yet they face persistent challenges from infectious diseases, metabolic disorders, and environmental stressors [1, 2]. These factors collectively reduce productivity, compromise animal welfare, and increase dependency on antimicrobial agents. In recent years, there has been growing recognition that animal health is not governed solely by pathogen exposure or genetics but is strongly influenced by nutritional status and its interaction with molecular and cellular regulatory systems. Animal nutrition plays a central role in maintaining immune competence by supplying essential substrates required for cellular metabolism, immune cell proliferation, and the synthesis of signaling molecules. At the same time, advances in molecular

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biology have revealed that immune responses are tightly regulated by complex gene networks that respond dynamically to internal and external stimuli [1, 3, 4].

Among emerging biotechnological approaches, recombinant proteins have gained attention for their ability to precisely modulate immune function and enhance disease resistance. These biologically engineered molecules, including cytokines, peptides, and functional proteins, can be used to mimic or enhance natural immune signals in livestock [5, 6]. Parallel to this, nested gene regulation represents a sophisticated genomic architecture in which genes embedded within larger gene structures contribute to fine-tuned regulatory control of immune responses. Such hierarchical gene systems allow organisms to respond efficiently to nutritional and pathogenic cues by adjusting gene expression patterns. Importantly, nutrient sensing pathways interact closely with these molecular regulatory networks, influencing immune signaling cascades, inflammatory responses, and metabolic homeostasis [2, 4, 7–9].

Despite advances in recombinant protein applications and gene regulation research, there remains a limited integrated understanding of how nutrient driven immune modulation interacts with nested gene regulation to influence disease resistance in livestock. Most existing studies focus on isolated components, such as nutrition, genetics, or biotechnology, without adequately addressing their combined effects. This study uniquely integrates recombinant protein biology with nested gene regulatory mechanisms under the framework of nutrient driven immune responses. It highlights how dietary inputs can influence molecular immune pathways and enhance the functional efficiency of recombinant proteins in improving disease resistance. By bridging nutritional science with advanced gene regulatory and protein engineering concepts, this work provides a more holistic perspective for developing innovative, sustainable, and precision based strategies for improving livestock health and resilience.

METHODOLOGY

A comprehensive narrative review methodology was adopted to synthesize current knowledge on recombinant proteins, nested gene regulation, and nutrient driven immune responses in livestock. Relevant peer reviewed articles were systematically identified from major scientific databases including PubMed, Scopus, Web of Science, and Google Scholar using targeted keywords such as animal nutrition, recombinant proteins, nested genes, immune response, disease resistance, and livestock health. Studies published in English over the past two decades were prioritized, with additional inclusion of seminal earlier works where necessary. Selected literature was screened based on relevance to molecular mechanisms, nutritional modulation, and immunological outcomes in livestock species including dairy cattle, beef cattle, poultry, and swine. Data were extracted and thematically organized into key domains, including nutrient sensing pathways, gene regulatory networks, recombinant protein applications, and immune system modulation. A qualitative synthesis approach was employed to integrate findings across disciplines, identify mechanistic linkages, and highlight knowledge gaps. The conceptual framework was developed based on converging evidence from molecular biology, animal nutrition, and immunology to illustrate the interactions driving disease resistance in livestock systems.

NUTRIENT DRIVEN REGULATION OF IMMUNE RESPONSES

Macronutrients and Immune Competence

Macronutrients, including proteins, carbohydrates, and lipids, play a foundational role in supporting immune competence in livestock. Proteins provide amino acids necessary for the synthesis of antibodies, cytokines, and immune cell receptors. Carbohydrates supply energy required for rapid proliferation and activation of immune cells during infection or vaccination. Lipids, particularly essential fatty acids, contribute to membrane structure and influence the production of lipid mediators involved in immune signaling. An imbalance in macronutrient supply can impair immune function, reduce resistance to disease, and negatively affect overall productivity and physiological resilience in animals [10–12].

Micronutrients in Immune Signaling Pathways

Micronutrients – such as vitamins and trace minerals – are critical regulators of immune signaling pathways in livestock. Vitamins A, D, and E are involved in immune cell differentiation, antioxidant defense, and modulation of inflammatory responses. Trace elements, like zinc, selenium, and copper, act as cofactors for enzymes that regulate oxidative stress and immune cell function. These micronutrients influence signal transduction pathways that control cytokine production and pathogen recognition. Deficiencies or imbalances in micronutrient supply can disrupt immune signaling networks, leading to weakened immune responses and increased susceptibility to infectious diseases [13–17].

Nutrient Sensing Mechanisms in Immune Cells

Immune cells possess specialized nutrient sensing mechanisms that allow them to detect and respond to changes in metabolic availability. Key pathways – such as mTOR, AMPK, and insulin signaling – regulate immune cell growth, differentiation, and functional activity based on nutrient status. These sensing systems integrate signals from glucose, amino acids, and lipids to adjust immune responses according to energy availability. When nutrients are sufficient, immune activation is enhanced, whereas nutrient scarcity leads to immune suppression or conservation mode. This dynamic regulation ensures metabolic efficiency while maintaining host defense under varying physiological conditions [18–21].

Regulation of Inflammation and Cytokine Balance

Nutrient availability plays a crucial role in regulating inflammation and maintaining cytokine balance in livestock. Balanced nutrition supports the controlled production of pro inflammatory and anti-inflammatory cytokines, ensuring effective pathogen clearance without excessive tissue damage. Specific nutrients can modulate signaling pathways, such as NF kappa B and JAK STAT, which govern cytokine expression. Overnutrition or malnutrition can disrupt this balance, leading to chronic inflammation or immune suppression. Proper dietary management helps stabilize cytokine networks, improve immune homeostasis, and enhance resilience against infectious and metabolic diseases [22–24].

NESTED GENE REGULATION AND MOLECULAR CONTROL OF IMMUNITY

Gene networks Controlling Immune Response

Gene networks controlling immune response consist of interconnected genes that coordinate innate and adaptive immunity in livestock (Figure 1). These networks regulate processes such as pathogen detection, immune cell activation, cytokine production, and antibody synthesis. Transcription factors and signaling molecules act as regulatory hubs that integrate external stimuli and internal physiological signals. The coordinated expression of immune related genes ensures a rapid and effective defense against infectious agents. Disruption in these networks can lead to immune dysfunction, increased disease susceptibility, and reduced productivity in livestock systems [25–27].

Epigenetic and Transcriptional Regulation

Epigenetic and transcriptional regulation play a crucial role in controlling immune gene expression without altering the underlying DNA sequence. Mechanisms (such as DNA methylation, histone modification, and chromatin remodeling) influence the accessibility of immune related genes [28–30]. These processes determine whether specific genes are activated or silenced in response to environmental and nutritional cues. Transcriptional regulation further refines immune responses by controlling the rate at which genes are transcribed into RNA. Together, these mechanisms provide flexibility and adaptability to the immune system, allowing livestock to respond efficiently to pathogens and changing physiological conditions.

Interaction of Nested Genes with Metabolic Signals

Nested genes interact closely with metabolic signaling pathways to integrate immune and nutritional status in livestock. Metabolic signals derived from glucose, amino acids, and lipid metabolism influence the activity of regulatory genes embedded within larger genomic structures. These interactions ensure that immune responses are aligned with energy availability and metabolic capacity. When nutrient levels are sufficient, immune gene expression is enhanced, whereas energy scarcity may suppress certain immune functions to conserve resources. This coordination between metabolism and gene regulation is essential for maintaining immune efficiency and physiological balance (Figure 1) [25–27].

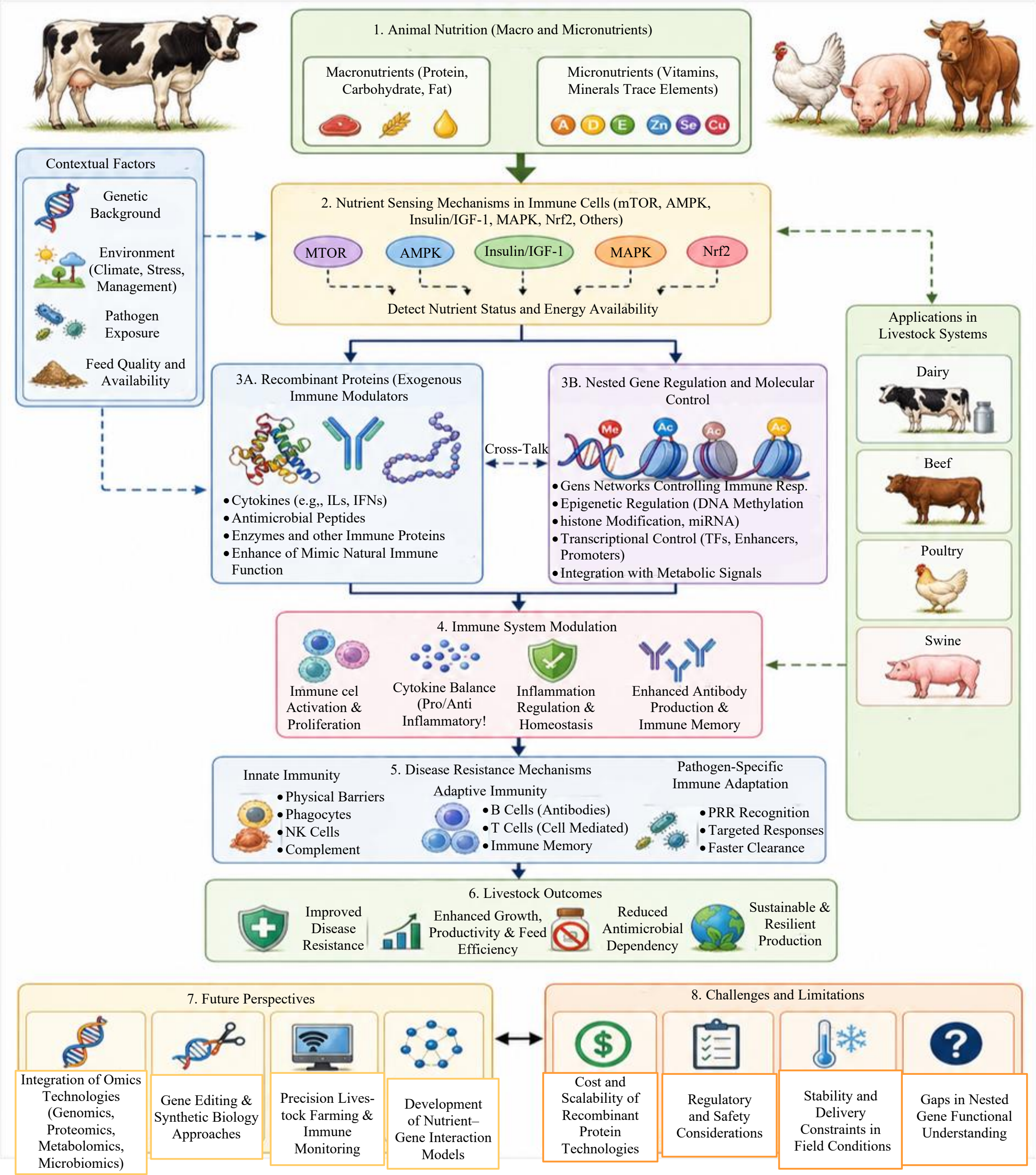

Figure 1. Conceptual framework of nutrient driven immune regulation through recombinant proteins and nested gene networks in livestock.

Role in Pathogen Recognition and Defense

Nested gene regulation contributes significantly to pathogen recognition and immune defense mechanisms in livestock. Genes involved in pattern recognition receptors, such as toll like receptors, are tightly regulated to ensure accurate detection of microbial invaders. Once pathogens are recognized, nested gene networks activate downstream signaling cascades that initiate inflammatory and adaptive immune responses.

This regulation ensures a rapid yet controlled defense reaction, minimizing tissue damage while eliminating pathogens. Efficient gene regulation in pathogen recognition pathways is, therefore, critical for improving disease resistance and overall health in livestock populations [28–30].

NUTRITION, RECOMBINANT PROTEINS, AND GENE REGULATION-INTERACTION

Nutrient Influence on Recombinant Protein Expression

Nutritional status directly affects the synthesis, stability, and functional expression of recombinant proteins in animal systems. Adequate levels of amino acids, energy sources, and micronutrients are essential for efficient protein translation and post translational modification. Nutrients also regulate cellular machinery involved in protein folding, secretion, and glycosylation, which are critical for recombinant protein functionality. In livestock applications, nutrient deficiencies can reduce the efficacy of recombinant protein-based interventions by impairing expression systems or altering protein structure. Therefore, optimized nutrition is necessary to maximize the biological activity and therapeutic potential of recombinant proteins [31–33].

Cross Talk Between Dietary Factors and Gene Regulatory Networks

Dietary components interact with gene regulatory networks through signaling pathways that control transcription, translation, and epigenetic modifications. Nutrients – such as fatty acids, amino acids, and vitamins – influence key regulators like mTOR, AMPK, and nuclear receptors, which in turn modulate gene expression patterns related to immunity and metabolism. This cross talk ensures that gene activity is aligned with nutrient availability and physiological demand. In livestock, such interactions help maintain immune readiness while preventing metabolic imbalance, thereby supporting both productivity and health under varying environmental and dietary conditions [34–36].

Modulation of Immune Response Efficiency

The combined influence of nutrition and gene regulation significantly enhances the efficiency of immune responses in livestock. Adequate nutrient supply supports rapid immune cell activation, cytokine production, and antibody synthesis, while gene regulatory networks ensure precise control of these processes. Recombinant proteins can further amplify immune signaling by mimicking or enhancing natural immune mediators. Together, these factors improve the speed, strength, and accuracy of immune responses against pathogens. This integrated modulation reduces disease incidence and improves recovery outcomes in livestock populations [37–40].

Synergistic Effects on Disease Resistance

Synergistic interactions between nutrition, recombinant proteins, and gene regulation result in enhanced disease resistance in livestock. Nutrients provide the metabolic foundation for immune function, gene regulatory networks ensure adaptive and controlled responses, and recombinant proteins offer targeted immunological support. When functioning together, these components create a reinforced defense system that improves pathogen clearance and reduces susceptibility to infections. This synergy also contributes to long term immune resilience and productivity stability. Such integrated strategies represent a promising approach for developing sustainable and disease resistant livestock production systems [41–44].

DISEASE RESISTANCE MECHANISMS IN LIVESTOCK

Innate and Adaptive Immune Responses

Innate immunity represents the first line of defense in livestock, providing rapid but nonspecific protection against invading pathogens. It includes physical barriers such as skin and mucosal surfaces, as well as cellular components like macrophages, neutrophils, and natural killer cells. Adaptive immunity, in contrast, is highly specific and develops over time through exposure to pathogens or vaccination. It involves lymphocytes, including T cells and B cells, which generate memory responses and antibodies. The interaction between these two immune arms ensures both immediate protection and long-term immunity, forming the foundation of disease resistance in animals [45–48].

Genetic Resistance vs Nutritionally Enhanced Resistance

Genetic resistance refers to inherent traits within livestock that confer natural protection against specific diseases, often governed by immune related genes and selective breeding. In contrast, nutritionally enhanced resistance arises from dietary strategies that improve immune competence and physiological resilience [49–52]. Nutrients influence immune cell function, gene expression, and metabolic pathways, thereby strengthening the host defense system. While genetic resistance provides a stable baseline of protection, nutritional interventions can modulate and enhance immune performance. The integration of both approaches is essential for improving overall disease resistance in modern livestock production systems.

Role of Inflammatory Cytokine Control

Inflammatory cytokines play a central role in regulating immune responses and determining disease outcomes in livestock. These signaling molecules coordinate immune cell activation, recruitment, and pathogen elimination. However, excessive or prolonged cytokine production can lead to tissue damage and chronic inflammation, reducing animal productivity and health. Nutritional status and genetic regulation significantly influence cytokine balance by modulating pathways such as NF kappa B and JAK STAT signaling. Effective control of inflammatory cytokines ensures an appropriate immune response that is strong enough to eliminate pathogens but regulated enough to prevent harmful overreaction [53–56].

Pathogen Specific Immune Adaptation: Limitations, Trade-offs, and Emerging Precision **Approaches**

Pathogen-specific immune adaptation in livestock is strongly influenced by nutrient-responsive recombinant proteins and nested gene regulatory networks; however, considerable interspecies and interindividual variability exists in immune responsiveness, metabolic efficiency, and disease resilience. Ruminants, swine, poultry, and aquaculture species differ markedly in gut architecture, microbiome composition, antigen recognition pathways, and cytokine signaling dynamics, which may alter the efficacy of nutrient-mediated immune modulation. For example, recombinant cytokines, antimicrobial peptides, and nutrient-sensitive transcriptional regulators may exhibit distinct immune-physiological outcomes depending on species-specific differences in Toll-like receptor signaling, epithelial barrier function, and metabolic partitioning. Furthermore, environmental stressors including heat stress, pathogen load, production intensity, and nutritional imbalance can modify gene expression patterns and compromise adaptive immune efficiency. These limitations indicate that universal immune intervention strategies may not be equally effective across livestock systems.

Another important consideration involves immune trade-offs associated with prolonged or excessive activation of nutrient-driven immune pathways. Enhanced immune stimulation often requires substantial metabolic resources, potentially diverting nutrients away from growth, reproduction, lactation, and feed efficiency. Chronic activation of inflammatory cascades may also induce oxidative stress, tissue damage, intestinal dysbiosis, or immunopathology, thereby reducing long-term productivity and animal welfare. In some cases, excessive expression of recombinant immune proteins or sustained activation of NF-kB, JAK-STAT, MAPK, and inflammasome-associated pathways may increase susceptibility to metabolic disorders or impair tolerance to environmental stress. Therefore, optimizing immune resilience requires balanced regulation between host defense, metabolic homeostasis, and productive performance.

Recent advances in precision livestock immunology provide promising opportunities to overcome these challenges. Multi-omics technologies including genomics, transcriptomics, proteomics, metabolomics, epigenomics, and microbiomics are increasingly being integrated to characterize pathogen-specific immune signatures and nutrient-responsive regulatory networks. These approaches enable identification of biomarkers associated with disease resistance, immune competency, and resilience under environmental stress. Systems biology and artificial intelligence-assisted modeling further facilitate prediction of host-pathogen interactions and dynamic immune responses across different production conditions. Additionally, novel immunomodulatory strategies – such as recombinant cytokines, engineered probiotics, phytobiotics, postbiotics, RNA-based therapeutics, nanoparticle delivery systems, and precision nutritional supplementation – are emerging as powerful tools to enhance disease resistance while minimizing immune-associated metabolic burdens. Integration of omics-guided biomarker discovery with targeted recombinant protein technologies may ultimately support development of precision feeding and immunomodulation programs tailored to species, genotype, physiological stage, and pathogen exposure in sustainable livestock production systems. Future research should focus on integrating recombinant protein engineering, systems immunology, and precision nutrition to develop species-specific immune adaptation strategies with minimal metabolic trade-offs [56–60].

Applications in Livestock Production Systems

The integration of recombinant proteins, nested gene regulation, and nutrient driven immune modulation has significant applications across diverse livestock production systems. These approaches are increasingly being adopted to improve animal health, productivity, and sustainability in dairy, beef, poultry, and swine industries. By combining molecular biotechnology with advanced nutritional strategies, production systems can achieve enhanced disease resistance, improved feed efficiency, and reduced reliance on antimicrobial agents. This integration supports the transition toward more resilient and efficient livestock production models under changing environmental and disease pressures [61–64].

Dairy, Beef, Poultry, and Swine Systems

The application of recombinant proteins and nutrient-responsive gene regulatory mechanisms in livestock production systems has demonstrated substantial improvements in productivity, immune competence, and disease resistance across multiple species. In poultry, dietary immunomodulatory proteins, probiotic-derived bioactive peptides, and amino acid-mediated immune regulation have been associated with 4–12% improvements in feed conversion ratio, 6–18% increases in average daily gain, and significant reductions in enteric pathogen colonization, including *Salmonella* and *Clostridium perfringens*. Similarly, supplementation strategies targeting cytokine-mediated intestinal immunity have been reported to reduce mortality by approximately 10–25% under pathogenic challenge conditions.

In swine production, recombinant enzymes, functional amino acids, and immune-regulatory peptides have improved nutrient digestibility by 5–15%, enhanced gut barrier integrity, and reduced post-weaning diarrhea incidence by up to 30%. In dairy cattle, nutrient-sensitive immune signaling pathways associated with recombinant lactoferrin, antimicrobial peptides, and trace mineral regulation have contributed to lower somatic cell counts, 15–35% reductions in mastitis incidence, and measurable improvements in milk yield and reproductive efficiency under stress conditions. Furthermore, precision nutritional modulation of immune pathways has been associated with enhanced vaccine responsiveness, improved oxidative stability, and reduced inflammatory biomarkers in heat-stressed livestock.

Emerging integration of omics-guided nutritional interventions and recombinant immunobiologics further supports development of precision livestock systems capable of simultaneously improving feed efficiency, pathogen resistance, animal welfare, and environmental sustainability. Collectively, these quantitative outcomes highlight the translational potential of recombinant proteins and nested gene regulation as next-generation strategies for resilient and sustainable animal production systems [65–68].

Precision Nutrition Approaches

Precision nutrition involves the targeted formulation of diets based on genetic, physiological, and environmental characteristics of livestock. This approach ensures optimal nutrient supply to support immune function, metabolic efficiency, and growth performance. By aligning nutrient delivery with specific biological needs, precision nutrition enhances the effectiveness of immune regulation and molecular interventions. It also allows for better utilization of feed resources and reduces waste output. The integration of data driven technologies and nutritional modeling further strengthens decision making in livestock management, leading to improved health outcomes and production efficiency [69–72].

Functional Feeds and Bioactive Compounds

Functional feeds enriched with bioactive compounds – such as peptides, probiotics, prebiotics, and plant derived phytochemicals – play a critical role in enhancing immune responses in livestock. These compounds modulate gut microbiota, improve nutrient absorption, and regulate inflammatory pathways. Bioactive feed ingredients can also influence gene expression and support the activity of recombinant proteins involved in immune regulation. Their inclusion in diets helps strengthen disease resistance and improve overall physiological resilience. Functional feeds represent a practical and scalable approach for enhancing animal health through nutritional biotechnology [73–76].

Integration with Breeding Programs

The integration of nutritional strategies and molecular technologies with breeding programs enhances genetic improvement for disease resistance and productivity traits. Selective breeding can be combined with genomic information related to immune function and metabolic efficiency to develop more resilient livestock populations. Nutritional interventions further optimize the expression of desirable genetic traits by supporting metabolic and immune pathways. This combined approach enables the development of animals that are both genetically and nutritionally optimized for health and performance. Such integration is essential for advancing sustainable and precision-based livestock production systems [77–80].

CHALLENGES AND LIMITATIONS

Cost and Scalability of Recombinant Protein Technologies

One of the primary limitations of recombinant protein applications in livestock is the high cost associated with production, purification, and formulation. Manufacturing biologically active proteins requires sophisticated biotechnological infrastructure, controlled expression systems, and stringent quality assurance processes. These factors significantly increase production expenses, making large scale application challenging, particularly in low- and middle-income livestock systems. Scalability remains a concern, as maintaining consistent protein quality and activity at commercial volumes is technically demanding. As a result, cost effectiveness and production efficiency are critical barriers to widespread implementation.

Regulatory and Safety Considerations

Recombinant proteins and gene-based interventions in livestock are subject to strict regulatory frameworks to ensure animal, human, and environmental safety. Regulatory approval processes often require extensive testing for toxicity, immunogenicity, and long-term effects. Concerns also exist regarding potential residues in animal products and unintended ecological impacts. Variability in regulatory standards across different countries further complicates global adoption. These safety and regulatory requirements, while essential, can delay product development and commercialization, limiting the speed at which innovations reach practical livestock systems.

Stability and Delivery Constraints in Field Conditions

The practical application of recombinant proteins and bioactive molecules in livestock is often hindered by stability and delivery challenges under field conditions. Many protein-based compounds are sensitive to temperature, pH, and enzymatic degradation, which reduces their effectiveness outside controlled laboratory environments. Ensuring proper delivery through feed, water, or injection systems requires specialized formulations and technologies. Inconsistent storage conditions and limited cold chain infrastructure in rural livestock systems further reduce stability. These constraints limit the reliability and efficiency of advanced molecular interventions in real world farming conditions.

Gaps in Nested Gene Functional Understanding

Although nested gene regulation is recognized as an important component of immune and metabolic control, significant gaps remain in understanding its functional mechanisms in livestock. The complexity of gene interactions limited species-specific genomic data, and incomplete annotation of regulatory networks hinder detailed interpretation. The functional roles of many nested gene structures in immune responses and disease resistance are still unclear. Additionally, the interaction between nested genes, nutrition, and recombinant protein activity remains insufficiently explored. These knowledge gaps restrict the ability to fully exploit genetic regulation for improving livestock health and productivity.

FUTURE PERSPECTIVES

Integration of Omics Technologies

The integration of genomics, transcriptomics, proteomics, metabolomics, and microbiomics offers a comprehensive framework for understanding immune and metabolic regulation in livestock. These omics technologies enable the identification of key genes, proteins, metabolites, and microbial populations involved in disease resistance and nutrient utilization. By combining multi-layer biological data, researchers can better characterize how nutrition influences gene expression and immune function. This integrated approach supports the discovery of biomarkers for health status and productivity, enabling more accurate selection and management strategies in livestock systems.

Gene Editing and Synthetic Biology Approaches

Gene editing technologies – such as CRISPR based systems and synthetic biology approaches – provide powerful tools for improving disease resistance and immune efficiency in livestock. These methods allow precise modification of genes involved in immune regulation, metabolic pathways, and pathogen recognition. Synthetic biology further enables the design of novel biological systems, including engineered recombinant proteins with enhanced functionality. These technologies offer the potential to develop livestock with improved resilience to diseases and better adaptation to environmental stressors. However, their application must be carefully evaluated for safety, ethics, and regulatory compliance.

Precision Livestock Farming and Immune Monitoring

Precision livestock farming integrates sensor technologies, data analytics, and real time monitoring systems to track animal health, behavior, and physiological status. In the context of immune regulation, continuous monitoring of biomarkers, such as temperature, feed intake, and metabolic indicators, can provide early detection of disease onset. This allows for timely nutritional or therapeutic interventions that enhance immune response efficiency. The use of digital technologies also enables individualized management of animals based on their specific health and nutritional needs, improving overall herd performance and disease control.

Development of Nutrient Gene Interaction Models

The development of nutrient gene interaction models is essential for understanding how dietary components influence gene expression and immune function in livestock. These computational and systems biology-based models integrate nutritional data with genomic and metabolic information to predict biological responses. Such models can help identify optimal feeding strategies that enhance immune competence and disease resistance. They also provide insights into the complex interactions between nutrients, gene regulatory networks, and recombinant protein activity. Advancing these models will support the development of precision nutrition systems tailored to genetic and environmental conditions in livestock production.

CONCLUSION

This study highlights the integrated role of recombinant proteins, nested gene regulation, and nutrient driven immune modulation in shaping disease resistance in livestock. Animal health is not governed by isolated nutritional, genetic, or molecular factors, but rather by a coordinated network of metabolic, immunological, and genomic interactions. Nutrients act as fundamental regulators of immune competence by influencing gene expression, cellular signaling, and inflammatory balance, while recombinant proteins provide targeted enhancement of immune pathways. Nested gene regulatory systems further refine these responses by enabling precise control of immune related gene networks under varying physiological and environmental conditions.

The synthesis of these components demonstrates that effective disease resistance in livestock depends on the dynamic interaction between diet, molecular biology, and immune system architecture. Improved understanding of these interactions provides a foundation for developing more efficient strategies for controlling infectious diseases, reducing antimicrobial dependence, and enhancing productivity. However, challenges related to scalability, cost, regulatory frameworks, and incomplete knowledge of gene network functions still limit full practical implementation.

Future progress will depend on the integration of omics technologies, precision nutrition, gene editing tools, and advanced monitoring systems to build predictive models of nutrient gene immune interactions. Such advancements will enable more targeted and sustainable livestock management practices. Overall, this integrated framework provides a promising pathway toward improving livestock resilience, ensuring food security, and supporting sustainable animal production systems in the face of increasing global challenges.

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