

REVIEW ARTICLE

Nutritional Modulation of Immunity in Animals: Mechanisms, Strategies and Future Perspectives

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ABSTRACT

Nutrition is one of the major determinants of immune competence in animals; as it influences general physiological, strength disease resistance susceptibility to infections. There should be constant nutrients supply to the immune system to maintain its function in cell proliferation, signal transduction pathways and effector functions. In recent years, considerable attention has been focused to make nutritional strategies to enhance immune function, vaccine efficacy and reduce reliance on antibiotics in animal production systems. Whereas, vitamins and trace minerals regulate immune signaling pathways, gene expression and antioxidant protection, macronutrients such as protein, lipids and carbohydrates provide structural components and metabolic support. Functional feed additives such as probiotics, prebiotics, phytochemicals and β -glucans possess an enormous potential for modulating both systemic and gut-associated immunity. This paper integrates current knowledge on the influence of nutrition in regulating immune system of livestock and pet animals, underlying mechanisms and practical feeding strategies. Emerging concept of precision nutrition and nutrigenomics are also here. The integration of the immune system in the overall health management in animals can provide sustainable health and nutrition solutions in line with One Health approach.

KEYWORDS

• Nutrition • Probiotics • Trace Minerals • Animal Health • Gastrointestinal Health • Livestock • Immune Nutrition and Immune Modulation

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INTRODUCTION

The immune system is a complex network of cells, tissues and organs which play a role in body defence and provides the animal body protection from pathogens and maintains homeostasis within the body. This body defence mechanism is dependent on genetic, environmental and nutritional influences. Of all these factors, nutrition is the most readily modified (Calder, 2022). In today's animal production, animal stress as a result of high stocking density, fluctuations in temperature, metabolic diseases compromises animal's immune competence. Nutritional deficiencies or imbalance can cause immune dysfunction and increase susceptibility to infection (Gombart *et al.*, 2020) whereas; other nutritional supplements may improve host defense and increase the resistance of diseases (Chauhan *et al.*, 2024).

Antimicrobial resistance is one of the major global concern; thus there is paradigm shift from therapeutic to preventative approaches. Nutritional immune modulation provides a suitable and sustainable solution that involves improving the intrinsic defense mechanisms of an animal (FAO, 2023) instead of relying solely on antibiotic treatment.

THE IMMUNE SYSTEM OF ANIMALS: AN OVERVIEW

1. Innate Immunity

Innate immunity is the first line of defense and utilizes rapid, non-specific mechanisms to eliminate pathogens. These include physical barriers like skin, mucosa membranes and cellular components like neutrophils, macrophages and dendritic cells (Abd El-Hack *et al.*, 2022).

Innate immunity efficiency is directly influenced by an animal's nutritional status. Nutritional deficiencies or imbalances of antioxidants contribute to higher oxidative stress levels leading to compromised phagocytic activity in clearing the pathogens (Surai, 2023).

2. Adaptive Immunity

The adaptive immune system includes B lymphocytes put in last and T lymphocytes responsible for antibody production and cell-mediated respectively. Antigen-specific and immunological memory is provided by

adaptive immune system which is influenced by nutrients at the following levels:

- Lymphocyte proliferation
- Cytokine production
- Antibody synthesis (Li & Wu., 2022).

Deficiencies in nutrients can impair immune maturation, especially of young animals, leading to a reduction in response to vaccination and long-term immunity (Chauhan *et al.*, 2025).

MECHANISMS OF NUTRITIONAL IMMUNOMODULATION

- **Gene Expression Control:** The level and action of certain nutrients regulate transcription factors such as NF-B and cytokine genes (Calder, 2022).
- **Antioxidant Protection:** Vitamin and trace minerals such as Se and vitamin E contribute to the antioxidant system and protect immune cells from being harmed by oxidation (Surai, 2023).
- **Cell Communication:** The cellular functions such as cell signaling pathways and intercellular communications among immune cells are regulated by fatty acids and amino acids (Li & Wu., 2022).
- **Interaction with Gut Microbiota:** Feeding behavior has direct influence on the composition of the microbial population in the gut, which indirectly interacts with the immune responses (Pluske *et al.*, 2023).

ROLE OF MACRONUTRIENTS IN IMMUNE FUNCTION

1. Proteins and Amino Acids

Proteins play an essential role in cell proliferation, development and function of immune cells (Li & Wu., 2021). The role of individual amino acids as regulatory nutrients in immunity include:

- **Glutamine:** It is an energy substrate for lymphocytes and enterocytes; it also supports gut associated lymphoid tissue (GALT).
- **Arginine:** Stimulates the production of nitric oxide to enhance the ability of macrophages to kill and support the immune system.

- **Sulfur containing amino acids (methionine, cysteine):** act as the precursors for the synthesis of glutathione, an antioxidant of major importance.

Protein deficiency has an adverse effect on the integrity of the immune system (Gombart *et al.*, 2020).

2. Lipids and Fatty Acids

Lipids play both structural and regulatory roles in the immune system.

- Omega-3 fatty acids (EPA, DHA) suppress inflammatory mediator generation via the modification of eicosanoid metabolism.
- Omega-6 fatty acids stimulate inflammatory responses needed to clear pathogens.

The balance between the proportions of omega-3 and omega-6 fatty acids determines the direction and amplitude of the immune response (Calder, 2022).

3. Carbohydrates

Carbohydrates are vital meeting the increased energy requirements during the immune response.

- Functional carbohydrates such as β -glucans can boost innate immune responses by activating macrophages and natural killer (NK) cells (Abd El-Hack *et al.*, 2022).

ROLE OF SMALL NUTRIENTS IN IMMUNE CONTROL

1. Vitamins

Vitamins act as important regulators of various immune by supporting immunocytes development and maintenance of immune response.

- **Vitamin A** is important in the development of mucosal immunity (Gombart *et al.*, 2020).
- **Vitamin D** activates antimicrobial peptide production (Calder, 2022).
- **Vitamin E** has a role as an antioxidant (Surai, 2023).
- **Vitamin C** facilitates phagocytic activity.
- Vitamin deficiency leads to compromised immune system and higher risk of diseases (Gombart *et al.*, 2020).

2. Trace Minerals

Trace minerals serve as cofactors different enzyme and immune processes:

- **Zinc:** Plays a crucial role in lymphocyte function (Kumar *et al.*, 2025).
- **Selenium:** Enhances antioxidant defense mechanism (Surai, 2023).
- **Copper:** Affects neutrophil activation.
- **Iron:** It's involvement in the regulation of immune cell proliferation.

Supplementation of trace minerals in the diet improves immune function and disease resistance (Kumar *et al.*, 2025).

FUNCTIONAL FEED ADDITIVES AND IMMUNITY

1. Probiotics:

These enhance gut health by restoring balance to gut microflora, improving mucosal immunity and antibody production (Abd El-Hack *et al.*, 2022).

2. Prebiotics and Synbiotics:

Prebiotics feed beneficial bacteria while synbiotics combine probiotics and prebiotics, offering synergistic effects (Pluske *et al.*, 2008).

3. Phytogetic Feed Additives:

Natural plant compounds such as allicin, curcumin, and essential oils possess antibacterial, antioxidant and immunomodulatory properties (Windisch *et al.*, 2008).

4. β -Glucans:

β -glucans have immunomodulatory capabilities, stimulating macrophages by binding with specific receptors, such as Dectin-1, to stimulate innate immunity (Abd El-Hack *et al.*, 2022).

GUT HEALTH AND IMMUNITY

The gastrointestinal tract plays a critical role in modulating the immune response harbours the majority of immune cells. Gut microbiota contribute to immunity by:

- Producing short-chain fatty acids (SCFAs)
- Modulating inflammatory responses
- Interacting with immune cells

Optimal gut integrity is crucial for efficient immune function.

NUTRITIONAL STRATEGIES IN LIVESTOCK

Dairy Animals:

- Antioxidants mitigate oxidative stress during the transition period (Surai, 2023).
- Balancing energy and protein ratios strengthens immune resilience (Chauhan *et al.*, 2025).

Poultry:

- Probiotics and phytochemical compounds bolster gut health (Abd El-Hack *et al.*, 2022).
- Micronutrient supplementation can enhance vaccine responses.

Small Ruminants:

- Mineral supplementation reduces the effects of parasites (Kumar *et al.*, 2025).
- Proper nutrition fortifies against GI infections.

Swine:

- Early life nutrition primes immune development.
- Functional additives alleviate post-weaning stresses (Pluske *et al.*, 2008).

Nutritional Immunology in Companion Animals

In companion animals, nutrition is increasingly being utilized as a therapeutic to support immune system.

Omega-3 fatty acids, antioxidants and amino acid-rich diets promote immune function and help manage chronic inflammation (Pluske *et al.*, 2008).

CHALLENGES AND LIMITATIONS

Despite promising outcomes, several challenges and limitations still issues persist:

- Species-specific variations in nutrient requirements
- complex among nutrients
- Limited field validation and
- Economic constraints for large-scale implementation (FAO, 2023).

FUTURE PERSPECTIVES

- **Precision Nutrition:** Individually tailored feeding plans based on genetics and health status are becoming prominent (Chauhan *et al.*, 2025).
- **Nutrigenomics:** Understanding nutrient-gene interactions will enable more targeted immune modulation (Calder, 2022).
- **Alternatives to Antibiotics:** Natural immunomodulators will be more important in reducing antibiotic use (FAO, 2023).
- **One Health Approach:** Healthier animals are essential for safer food systems, minimizing the risk of zoonoses (FAO, 2023).

CONCLUSION

Modulating immunity through nutrition is a viable and sustainable scientific approach to animal health. Optimal dietary composition and functional feed additives have the potential to improve immune responses, reduce diseases and mitigate reliance on antibiotics. Continued research and cross-discipline cooperation are required to bring these strategies to widespread field application.

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