

## Nutritional Strategies to Enhance Immunity in Poultry: A Review of Feed Additives and Dietary Formulations

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DOI: <https://doi.org/10.36347/sajb.2025.v13i02.006>

Received: 06.01.2025 | Accepted: 10.02.2025 | Published: 13.02.2025

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### Abstract

### Review Article

This review explores the effect of nutritional strategies on improving immunity in poultry with special emphasis on additives and diet formulations. Poultry immunity is sensitive to dietary components; nutrients such as antioxidants, essential fatty acids, probiotics, prebiotics, and phytochemicals are critical for modulating immune responses. Incorporating phytogenic feed additives and nutraceuticals into diets has quickly been perceived as a safe, natural strategy to boost poultry immunity. Finally, the emerging concept of precision nutrition, in which diets are designed specifically to the needs of the individual bird, provides a rationale for feeding specific nutrients to optimize immune function. Novel feed processing technologies, such as extrusion, fermentation, and encapsulation, also help improve the bioavailability of immune-enhancing nutrients. The review also pointed out that alternative protein sources like insects and algae fit into this category, making poultry health feasible for outstanding sustainability. The bioinformatics approach package will integrate various omics technologies and personalized nutrition science to specify further immune-enhancing dietary strategies. The extensive review highlights the role of nutrition in enhancing poultry immunity and insights into novel interventions in enhancing poultry health.

**Keywords:** Poultry nutrition, immune function, feed additives, immunomodulation, sustainability, omics technologies, poultry health.

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## 1. INTRODUCTION

Immunity is an important aspect for health and productivity in poultry; hence, it is very important in terms of commercial poultry farming. Chickens and turkeys are especially vulnerable to many infectious diseases and they can result in profound economic losses in the poultry sector (Alders *et al.*, 2018). These bacterial, viral, or parasitic diseases adversely affect bird health, farm productivity, feed efficiency, and can have an impact on public health with certain pathogens having zoonotic potential (Chintoan-Uta *et al.*, 2020). Thus, a

strong and efficient immune system plays an important role in poultry management during which birds are required to combat infection and restore homeostasis when exposed to environmental stressors (Meunier *et al.*, 2016).

Nutrition is one of the most important drivers of immune function among all factors that can modify immune function. Adequate nutrition is the basis for the maturation and activation of immune cells, antibody production, and regulation of inflammatory responses

**Citation:** Umber Rauf, Sadaqat Ali, Muhammad Sajid, Abid Ahmad, Waqas Mahmood, Obaid Muhammad Abdullah, Muhammad Nouman Azam, Qazal Hina, Muhammad Ali Assad, Hafiz Aftab Jan. Nutritional Strategies to Enhance Immunity in Poultry: A Review of Feed Additives and Dietary Formulations. Sch Acad J Biosci, 2025 Feb 13(2): 251-261.

(Abdel-Moneim *et al.*, 2020). Nutritional insufficiency or unbalance can impair immunity lead to increased infection risk and inability to recover from an illness in poultry. Hence, adopting poultry diets to provide a supportive environment for the immune system has become an important management strategy for modern poultry production (Surai *et al.*, 2021).

The positive impact of feed additives and nutritional compositions on poultry immunity has attracted more attention in recent years. These approaches aim to supplement the normal poultry ration with additional nutrients, functional compounds, and bioactive ingredients that will help modulate the immunological response (Parker *et al.*, 2021). These studies indicate that the use of feed additives like vitamins, minerals, probiotics, prebiotics, amino acids, and antioxidants is one of the methods that may help to enhance the immune system by improving gut health, modulating the oxidative stress response, and modulating the inflammatory processes essential for the function of the immune defense. Likewise, an optimized diet for a defined growth phase or environmental challenge may greatly influence the development and functionality of the poultry immune system (Rehman *et al.*, 2018).

This review is intended to investigate different nutritional strategies to improve poultry immunity with an emphasis on feed additives and dietary regimens. The recent discoveries will be reviewed regarding the impacts of individual dietary ingredients on components of the immune system and seek to offer an understanding of how such nutritional interventions can best be applied for enhanced health and productivity in poultry (Borda-Molina *et al.*, 2018). Lastly, the challenges and limitations and the future directions in this area which will also state the required improvement in poultry nutrition to ensure poultry farming continues as a sustainable farming system around the globe will be discussed (Johnson *et al.*, 2017).

## 2. The Role of Feed Additives in Poultry Immunity

Feed additives are additional components that can be added to poultry feeds, to promote their growth, health, and immunity. They are widely recognized in present-day poultry nutrition due to their mechanism of direct action on the immune system and resultant health status of the birds. These additives work by supplying nutrients, providing a local effect or nutrients for gut health modulation, modulators of oxidative stress, and modulators of immune response (Alagawany *et al.*, 2021). Different classes of feed additives such as vitamins, minerals, probiotics, prebiotics, antioxidants, essential fatty acids, phytogenic, and amino acids have shown great promise to enhance the immunity of poultry (Micciche *et al.*, 2018).

### 2.1 Vitamins and Minerals

Vitamins and minerals are crucial ingredients of poultry rations, and their function in immunity is well studied. For example, vitamins A, D, E and C, and minerals including zinc, selenium, and manganese are important for immune function. For instance, it maintains the integrity of mucosal surfaces e.g., the epithelial cells lining the respiratory and intestinal tracts, thus enhancing mucosal immunity. Vitamin D plays an important role in T-cell activation, a major arm of the adaptive immune system, and regulating the expression of different immune-associated genes. Vitamin E acts as an antioxidant that, together with selenium, provides protection to immune cells against oxidative damage; and vitamin C is important for collagen synthesis, in addition to supporting immune cells such as phagocytes and lymphocytes (Micciche *et al.*, 2018).

Zinc and selenium are especially important mineral elements for the regulation of immune responses. Numerous enzymes involved in DNA synthesis, protein synthesis, and cell division (important for immune cells) require zinc as a cofactor. Together with vitamin E, selenium protects the immune cells from oxidative stress and inflammation, and of course we know that oxidative stress and inflammation impair immune function (Micciche *et al.*, 2018).

### 2.2 Probiotics and Prebiotics

Gut health and immune function are closely related to each other in poultry. Intestinal microbiota is the first-line defense against pathogenic microorganisms, and the balance of gut flora is crucial to the optimum immune response (Micciche *et al.*, 2018). Probiotics are the healthy microorganisms that produce health effects when they are given in sufficient amount, have been proven to improve gut health which in turn leads to better immunity of poultry. Probiotics can outcompete pathogenic bacteria (pathogens), produce antimicrobial compounds, and enhance gut barrier defense to block pathogen invasion (Abd El-Hack *et al.*, 2020).

On the other hand, prebiotics are non-digestive food component that encourage production or function of favorable microorganisms in the gut. These consist primarily of oligosaccharides, inulin, and other similar fiber-containing agents (Micciche *et al.*, 2018). Recognizing that prebiotics are substrates for beneficial bacteria to improve the composition of gut microbiota and to enhance gut-associated lymphoid tissue (GALT) function, GALT is an essential part of the immune system (Teng and Kim, 2018).

### 2.3 Antioxidants

Antioxidants are compounds that respond with free radicals to reduce oxidative stress, which is a well-known cause of immune dysfunction. Antioxidants, including vitamin E, selenium and carotenoids (lutein and zeaxanthin), are crucial to protecting immune cells

in poultry from oxidative damage. The above chronic oxidative stress can deplete all the antioxidant nutrients we consume from food and cause our immune cells like macrophages and lymphocytes to stop functioning effectively, leading to susceptibility to infections (Alagawany *et al.*, 2021) (Micciche *et al.*, 2018).

The effect of antioxidant supplementation in poultry diets includes improving immune responses, decreasing incidence of infectious diseases, and enhancing overall health of the birds. These antioxidants can also aid in the formation of pro-inflammatory cytokines which play a critical role in the initiation of immune responses against infection (Alagawany *et al.*, 2021).

#### 2.4 Essential Fatty Acids

Omega-3 and omega-6 fatty acids are essential fatty acids (EFAs) that not only make up an important portion of poultry diets but also have an impact on aspects of immunocompetence. These fatty acids are involved in the production of eicosanoids, signaling molecules that regulate inflammation and immune cell functionality. Their anti-inflammatory properties and ability to boost cellular immunity can be attributed to the omega-3 fatty acids that come from fish oil and flaxseed. They regulate the inflammatory response, preventing excessive inflammation which would damage the immune response itself (Alagawany *et al.*, 2021).

In contrast, the omega-6 fatty acids derived from vegetable oils are involved in immune-cell activation and pro-inflammatory responses. Imbalanced ratio between omega-3 and omega-6 fatty acids effectively disrupts immune homeostasis, leading to an over-exuberant pro-inflammatory immune response and/or immune suppression (Alagawany *et al.*, 2021) (Micciche *et al.*, 2018).

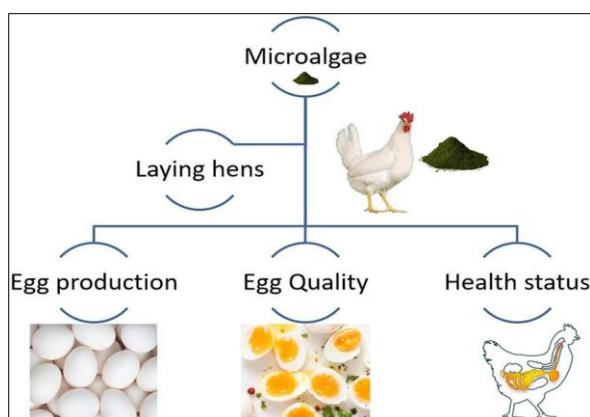
#### 2.5 Phytogetic

Phytogetic, also referred to as plant-based additives, have been recognized in poultry nutrition for their immune-modulating and other diverse healthful properties. These additives include things Well-known antioxidant, anti-inflammatory and antimicrobial compounds such as Essential oils, herbs and spices. Phytogetic such as garlic, oregano, thyme, and turmeric, have been demonstrated to improve the immune status of poultry through enhancement in the modulation of cytokine profile, improvement in gut status, and oxidative stress antioxidant capacity (Alagawany *et al.*, 2021).

These compounds also increase the general tolerance of these animals to pathogens, which translates into lower antibiotic usage and greater sustainability of poultry production. Being natural they are a good choice for farmers who want to reduce chemical additives in poultry diet (Alagawany *et al.*, 2021).

#### 2.6 Amino Acids

Amino acids — the building blocks of proteins — are vital for immune cells. A few amino acids like arginine, glutamine and threonine, have been recognized of special value for improving immunocompetence in poultry. One example is arginine, which participates in nitric oxide (NO) synthesis, a factor that is crucial for the activation of immune cells and the defense against pathogens. It supports the immune system where glutamine is used as fuel for lymphocytes and macrophages, as well as helping to have a healthy intestinal tract. When broiler or layer diets are supplemented with these amino acids, they exhibit a better immune response especially during stress or disease challenges (Micciche *et al.*, 2018, Alagawany *et al.*, 2021).



**Figure 1:** The diagram represents the points affected by microalgae supplementation in a laying hen diet accounting for egg production, egg quality, and health status. The green powder of microalgae in the study positively influenced these factors. It indicates a promising increase in the number of eggs for egg production and relates microalgae to beneficial parameters of egg production such as improved shell quality and nutritional value for egg quality. The diagram also emphasizes the benefits to the health condition of the hens with improved gut and immune system activity. The associations are further reinforced in this advertisement with images of eggs, boiled eggs and a chicken with its digestive system that links microalgae to these outcomes (Abdel-Wareth *et al.*, 2024)

### 3. Dietary Formulations to Support Immunity

Besides some specific feed additives, the general composition of poultry diets is an important factor that can affect immune function. A properly formulated diet specific to the nutritional demands of poultry, including growth stage, environmental stresses, and disease challenges, can have a substantial positive impact on the immune system function (Surai *et al.*, 2019). This is mainly owing to appropriate dietary formulation, which provides the right quantities of crucial nutrients in available forms that the birds need for efficient functioning of immune cells, and for proper immune response and health. This article reviews dietary strategies aimed at promoting immune health of poultry through consideration of stress, protein quality, energy supply, and specific formulation stages (Alders *et al.*, 2018).

#### 3.1 Formulation for Stress Management

Chicken is routinely exposed to numerous stressors, including environmental factors (e.g., temperature changes), transport, overcrowding, and infection. Increased levels of the stress hormone cortisol in stressful situations can suppress immune responses among birds, making them more vulnerable to infection. Thus, the need to formulate diets to help maintain immune resilience during stressful circumstances is vital (Haq *et al.*, 2016).

Nutritional strategies to manage stress comprise of the addition of certain vitamins, minerals, and antioxidants that help to counteract the impact of stress. Such as found for vit C, vit E (have effect to reduce oxidative stress & improved immune system response). Moreover, minerals like zinc and selenium also counteract the effects of stress through antioxidant defense systems and immune cell function (Haq *et al.*, 2016). Additionally, nutrients can be included in stress-lowering dietary formulations to aid immunity during times of stress, such as the amino acid glutamine, which is a source of energy for immune cells at times of physiological stress (Qaid and Al-Garadi, 2021).

#### 3.2 High-Quality Protein Sources

Immune cell, antibody, and many other immune system components are made out of proteins. This is why we need a lot of protein, especially to mount immune responses — to produce antibodies and active immune cells (Barekattain *et al.*, 2020). So, when designing poultry diets on high-quality protein sources, high-quality protein is supplied to the birds and high-quality protein portioned to their immune cells where they can achieve sufficient immune response (Bryan and Classen, 2020).

Animal proteins such as fish meal, meat and bone meal and blood meal, are usually regarded as higher quality protein sources for poultry because they have higher digestibility and contain essential amino acids in ideal ratios. Plant-based protein sources like

soybean meal and canola meal are often used so that animal protein sources like fish meal and blood meal are limited to fill the dietary protein needs because of costs and availability (Wang *et al.*, 2017). A careful balance of proteins is required, as deficiencies and excesses can lead to impaired immune response or metabolic stress, and so it is important that proper protein levels are maintained to boost immune function (Zaefarian *et al.*, 2021).

Immunity is also influenced by the digestibility of the proteins in the feed. Proteins that are not digestible will upset the nutrient balance, foregoing the production and functioning of immune cells. It is important to support the immune system's effectiveness through the use of highly digestible protein sources in diets, along with a proper balance of the essential amino acids (Alagawany *et al.*, 2021).

#### 3.3 Energy-Supplemented Diets

One vital means of supporting immune function in poultry is through energy intake. Eating enough carbohydrates and fats is necessary, as energy is an important source for immune cells. Energy metabolism: energy costs during immune activation (Akbarian *et al.*, 2016). Increased energy demand is placed on the immune system during acute immune activation, such as during infection or vaccination. Hence, providing poultry with enough energy from readily available sources is essential for immune cells to function normally and maintain health (Gelli *et al.*, 2019).

Sugars and starches are immediate fuels for the immune system, while fats, and especially essential fatty acids (omega-3 and omega-6), provide the building blocks for immune-modulating eicosanoids (Hu *et al.*, 2019). Fatty acids also facilitate the synthesis of lipids that are needed to create essential cell membrane components and structures of immune cells. By ensuring enough energy intake from both macronutrients (i.e. carbohydrates and fats), birds may have energy reserves to cover good immune function (Surai *et al.*, 2019).

Excessive energy consumption and serenity lead to weight gain and metabolic diseases, which can have adverse effects on immune responses. Therefore, the energy requirements of poultry must be considered in the diet formulation so that the energy level will not be excessive and cause stress on the immune system (Abo-Al-Ela *et al.*, 2021).

#### 3.4 Formulating for Specific Stages of Growth

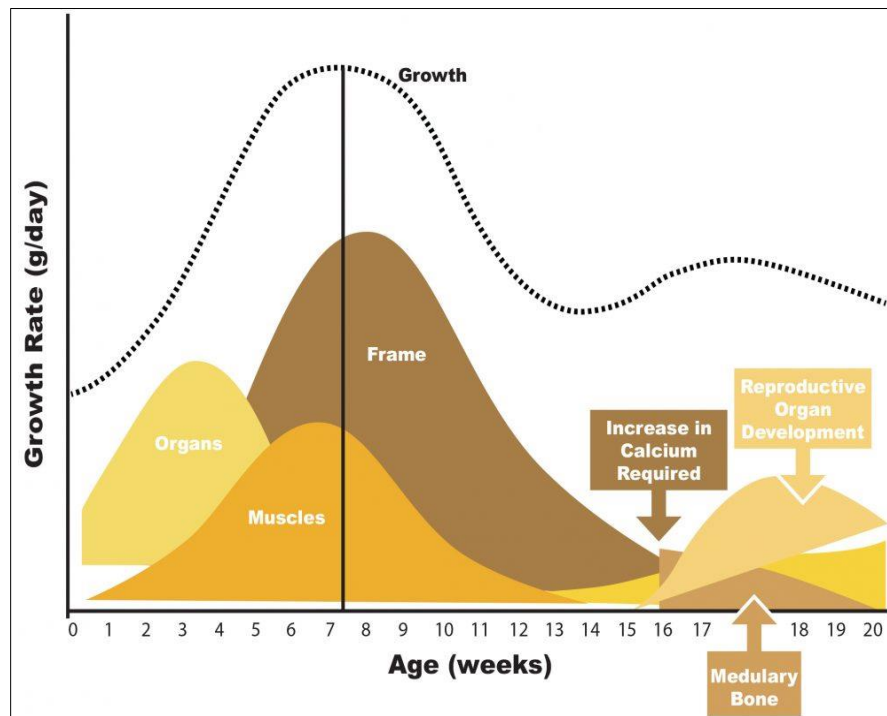
However, the nutritional requirements of poultry are very different at different life stages and the diet should be formulated to meet optimal immune function for each life stage. Chicks, grower birds and laying hens all have different nutritional needs which are critical at different stage of development for the immune system (Ratriyanto and Mosenthin, 2018).

**Chicks (0 to 3 weeks):** In the very beginning chick's life, immunity comes from colostrum (the first milk from the hen) and from the egg yolk but when eating solid feed, a high-quality diet is critical to encouraging good immune system development. A good immune base requires high-quality protein, as well as high levels of vitamins A, D and E, and minerals such as zinc and selenium (Ratriyanto and Mosenthin, 2018).

**Growers (3-10 weeks):** In the grow phase, immune responses are starting to develop, and energy needs increase. A properly composed diet should also be able to recruit enough protein for the immune cells to perform their necessary functions, and to contribute enough energy for the rest of the growth and development. Probiotics or prebiotics could also contribute to a better gut health, a key part of the immune function (Abd El-Hack *et al.*, 2020).

**Layers (10+ weeks):** Laying hens have very specific nutritional needs, as their immune system must remain strong and healthy to prevent infections while creating eggs. Laying hen diets should be based on high-quality protein and supplemented with feed additives, like antioxidants, that promote immune response while maintaining egg production. Omega-3 Fatty Acids Omega-3 fatty acids are also beneficial for egg quality as well as immune health (Gelli *et al.*, 2019).

Different life stages and ages require their own tailored balance of nutrients for ideal immune responses and health. When poultry receives complete and properly formulated diets they have the nutrients to build and maintain an optimally functioning immune system throughout their lives (Abo-Al-Ela *et al.*, 2021).



**Figure 2:** Points related to egg production, egg quality, and health status reflected the impact of microalgae supplementation in a laying hen diet as depicted in the diagram. Microalgae green powder showed an improvement on these factors as well. It shows a potential for rising the quantity of eggs for eggs production and correlates microalgae to key features of eggs production including shell quality and egg quality in terms of nutrition value. It also highlights the advantages of the gut and immunity activity of the hens for the health status of these animals. This advertisement also connects microalgae to these effects by showing images of eggs, boiled eggs and a chicken with its digestive system

#### 4. Limitations in Implementing Nutritional Strategies

Although nutrition can play an integral role in improving poultry immunity, a number of obstacles and limitations exist regarding the successful application of nutritional modulations in commercial poultry production. These challenges arise from the complexity of ante-mortem synthesizing the right diet, differences in the quality of feed, environmental stressors, costs associated with additives of feed, and more precision research on nutritional intervention. The main barriers to improving immune function using nutritional strategies

in poultry production will be considered, along with the shortcomings in knowledge and practice (Shojadoost *et al.*, 2021).

#### 4.1 Nutritional Imbalances and Diet Formulation Complexity

Establishing the appropriate quantities of nutrients to balance the preparation of nutritionally complete diets that promote optimal immune functionality. The answer is not only just protein, fats, carbohydrates, vitamins, minerals and bioactive

components, but to include them in adequate amounts to maintain growth and production and promote immune functioning (Shojadoost *et al.*, 2021). Poor supply of particular nutrients or over- or under-supply of other dietary factors may cause imbalances that either impair immune responses or harm overall health (Fouad *et al.*, 2019).

High levels of protein in poultry diets will cause nitrogen waste, increasing, in turn, the burden on the kidneys and, as a result, may impose metabolic stress, damaging immune function durability. On the other hand, inadequate protein or important amino acids including arginine and glutamine may impair immune cell functionality and also antibody manufacturing. In a same vein, an improper ratio of omega-3 to omega-6 fatty acids can disrupt immune homeostasis, resulting in excess inflammation or insufficient immune function (Fouad *et al.*, 2019).

In addition, some nutrients have complex interactions that need to be taken into account (Alagawany *et al.*, 2021). For instance, excessive calcium in poultry diets may impede the absorption of other minerals such as zinc and magnesium, both of which are important to immune response. And so getting the appropriate quantity of nutrients on the balance is a constant balancing act, combining elements of surveillance, formulation, and nimbleness when birds show signs of deteriorating health, environmental impacts and life cycle stage (Surai *et al.*, 2019).

#### 4.2 Variability in Feed Quality and Ingredient Sourcing

The composition and quality of the ingredients are vastly dependent on its source, which affects the quality in the final feed formulation of the poultry feed. Nutrient variability in feed ingredients is often influenced by external factors such as soil quality, harvesting methods, and post-harvest handling. Example plant-based ingredient whose vitamin and mineral nutritive value is subject to change given environmental, storage, and processing aspects—soy oil meal (Surai *et al.*, 2019).

In addition, differences in nutrient profile of feed ingredients lead to inconsistently supplying critical nutrient amount to birds. This may pose a challenge for producers to accurately design and formulate diets that provide consistent immune support. To achieve this, the usual practice of feed companies has undergone constant testing of feed for nutrient content and implementing quality control measures where concentration of nutrients in the feed is assured (Surai *et al.*, 2019).

The second parameter is the variability of available feed ingredients around the world. It is not easy to obtain good, immune-boosting additives and ingredients due to supply chain disruptions, price hikes, and restrictions of various ingredients from different

geographic backgrounds. Such variation can affect poultry producers from executing nutritional strategies (Surai *et al.*, 2019).

#### 4.3 Cost of Feed Additives

Cost of feed additives is one of the keys limiting factors in the application of nutritional strategies which have the prospects for enhancing poultry immunity. Feed additives (including probiotics, prebiotics, antioxidants and vitamins) can be extremely beneficial for poultry health and immune system function, but they are expensive (Table 1). The high cost of quality feed additives may be an obstacle for many poultry producers, especially from developing countries or with less financial capacity or with more sensitive issues (Abdel-Moneim *et al.*, 2020).

In addition, prices of feed additives can be subject to market and supply risks. The differences in cost may result in producers favouring economical feed additives which they can recover the costs in the short term, but may not have good long-term effects on poultry health. As a result, despite up-scaled immune enhancers potentially presenting opportunities for increasing immunity, their uptake could be compromised due to cost of turn-key high-grade additives (Ricke *et al.*, 2019).

Beyond the high price of some feed additives, not much is known about the required doses and combinations of additives that could best improve animal immunity. In the absence of clear directives and standardization on the composition of supplements, producers may avoid investing in various feed additives, leading to a further reduction in the use of these products in commercial poultry production (Abd El-Hack *et al.*, 2020).

#### 4.4 Environmental Stressors and Immune System Response

When it comes to poultry health and immune systems, several environmental factors play a role—extremes of temperature, humidity, air quality, housing conditions, etc. Cash and fellow researchers wrote that for example, heat stress under high ambient temperatures depresses the immune response, resulting in greater susceptibility to diseases such as avian influenza and Newcastle disease. Even if nutritional conditions are optimal, under such conditions, environmental stressors may overwhelm the birds' immune system functioning, leading to an inability to mount an immune response (Prasai *et al.*, 2016).

Although some nutritional strategies might help reduce the effects of environmental pressure, we cannot overcome the detrimental effects of poor housing conditions or very adverse environmental conditions. By way of example, while it should be possible to mitigate the effects of heat through added antioxidants in the diet, it would not solve the root causes of stress. As such,

poultry producers should consider a nutritional approach alongside sound management practices—temperature, ventilation, and stocking density—to help birds achieve the optimal level of immune performance (Saeed *et al.*, 2017).

In addition, environmental stressors may prevent feed intake, which would then have an impact on nutrient absorption and therefore affect the ability for birds to garner the nutrients necessary to maintain immune function. This indicates that an integrative strategy, providing nutrition with environmental modulation, is necessary for a better development of the immuno-competence of poultry (Nabi *et al.*, 2020).

#### 4.5 Limited Research on Long-Term Effects

Although there have been increasing studies on poultry immunity from a nutritional perspective, there remain a limited number of available long-term studies investigating such dietary practices. This has led a lot of the existing literature to focus on relatively short-term efficiency, e.g. early immune responses or pathogen-specific resistance. Nonetheless, the possible enduring impact of prolonged dietary supplementation on immune function, disease resistance, and overall flock health is an avenue currently being pursued (Fouad *et al.*, 2021).

In addition, most studies examine specific feed additives or nutritional strategies *in silico*, however, poultry diets are complex and contain various nutritional components. Conclusions: More comprehensive and long-term research that considers and studies the aggregate effects of different nutritional strategies on the immune health of the bird over its lifetime and their potential impact on farm production performance is warranted (Attia *et al.*, 2021).

Experimental studies on nutrition and immune interactions in accordance to the poultry sector are usually conducted under experimental conditions that do not necessarily reflect what is commonly faced in commercial production. However, the true commercial value and application of alternative dietary nutritional strategies against pathogens is challenged by their testing in laboratory settings which do not reflect diverse field conditions, and further research is required to explore this potential avenue of immunological enhancement under commercial conditions (Bhagwat *et al.*, 2021).

### 5. Future Directions and Emerging Trends in Poultry Nutrition for Immunity

With the continual advancement of the poultry industry, there is increasing demand for the discovery of another possible nutritional method in improving immunity in poultry. Given the current and future demands for poultry products likely escalating with increasing disease, stress, and environmental change concerns, the impact of nutritional strategies in improving immunity and flock health warrants further research and developments (Miller and Taylor Jr, 2016).

#### 5.1 Precision Nutrition and Personalized Diets

A promising approach to overcome the challenges for poultry health and the immune system comes with the development of precision nutrition, which involves the tailoring of diets in accordance with individual birds, or flocks. Precision nutrition is the application of advanced technologies, including sensors, data analytics, and genetic profiling, which are utilized to evaluate the specific nutritional needs of the birds according to their age, genetic make-up, health status, and environmental parameters (Zaefarian *et al.*, 2021).

An exciting area for precision nutrition will be the potential to provide individualized diets to individual birds or sub-groups of birds within a flock. This would enable poultry producers to mimic precise dietary formulations by using real-time data on feed intake, growth rates and immune markers of the birds throughout their entire phase. This tailored approach would provide birds with the optimal combination of nutrients to modulate immune function, and could also help decrease antibiotic and other drug use and improve overall flock health (Te Pas *et al.*, 2021).

Precision nutrition would also ensure that feed resources are not wasted and nutrients are utilized and absorbed as effectively as possible. Such a process enhances the immunity of poultry and forms a significant opportunity to mitigate the environmental footprint for poultry farming through reduced feed cost along with nutrient runoff (Zaefarian *et al.*, 2021).

#### 5.2 Functional Feed Ingredients

The addition of functional feed ingredients, which confer health advantages in addition to the basic nutritional value of diets, is a novel trend in poultry nutrition. Examples of such immune-modulating bioactives include phytochemicals, prebiotics, probiotics, and nutraceuticals (Micciche *et al.*, 2018).

**Plant-derived phytochemicals:** Many plant-based compounds like polyphenols, flavonoids, and alkaloids exhibit antioxidant, anti-inflammatory, and antimicrobial activity. Phytochemicals incorporated into poultry diets play an important role in modulating immune responses, mitigating oxidative stress and enhancing resistance to the disease. Current studies are done to explore the specific plant-based components that are more effective in enhancing immune function in poultry (Lv *et al.*, 2018).

**Prebiotics & probiotics:** Gut is the hub of immune activity and improvement in gut function has shown improved systemic immunity in poultry species. Prebiotics and probiotics are becoming ever more common components of poultry diets, with prebiotics being defined as food ingredients which induce the growth or activity of beneficial microorganisms that confer health benefits to the host and probiotics defined as live microbes that have beneficial effects for the host

animal when administered in adequate amounts. These components promote a healthy gut microbiome which then in turn leads to enhanced immune responses and prevents invasion by pathogens (Micciche *et al.*, 2018).

**Nutraceuticals:** Nutraceuticals are compounds that offer both nutritional as well as therapeutic benefits. Examples are omega eggs 3 fatty acids and well-tolerated plant extracts and peptides with the ability to promote immune function and fight inflammation. Nutraceuticals are potential alternatives in poultry feeding as an alternative to pharmaceutical ingredients (e.g., antibiotics) and in response to the strong consumer demand for antibiotic-free poultry products (Lv *et al.*, 2018).

Utilization of these functional feed ingredients in poultry diets is a promising strategy to improve immunity in a natural and sustainable way. Additional research on these elements will lead to more species-specific and more effective formulations for improving poultry health (Lv *et al.*, 2018).

### 5.3 Technological Innovations in Feed Processing

The rapid growth of feed processing technologies in recent years has opened several pathways to address the challenges of nutrient bioavailability and efficiency in poultry diets. There is an interest in exploring feed processing technologies (e.g. extrusion, fermentation, encapsulation) that can improve nutrient utilization, immune function, and reduce feed wastage (Zaefarian *et al.*, 2021).

**Extrusion:** Extrusion is a dry or wet method in which feed ingredients are addressed under high temperatures and high pressure and transformed into a particular shape. Extrusion enhances the digestibility of feed, making it easier for birds to gather more nutrients. This also may promote the bioavailability of some feed ingredients including probiotics and enzymes that have immune supporting properties (Zaefarian *et al.*, 2021).

**Fermentation:** Fermentation processes harness the ability of beneficial microorganisms to break down feed ingredients to more available and usable forms. Research on fermented feeds has revealed beneficial potential effects for gut health, nutrient digestibility, and immunity. In addition, the fermentation process of feeds may enhance its microbial content that leads to reduction of the pathogen load from the gut thereby improving the disease resistance as well (Zaefarian *et al.*, 2021).

**Encapsulation:** The technologies of encapsulation prevent sensitive nutrients and bioactive compounds from degrading during digestion and releasing specifically in certain sections of the gastrointestinal tract. Effective form for local application of probiotics, enzymes, and other immune-friendly ingredients. By encapsulating feed additives, the stability and effectiveness of the additives are improved, which can form better immune responses (Zaefarian *et al.*, 2021).

Future research on these feed processing technologies would focus on optimizing diets for poultry to achieve proper immune function by improving the bioavailability of nutrients or deriving chemical compounds, which will be used to derive novel bioactive.

### 5.4 Alternative Protein Sources and Sustainable Diets

The rapidly increasing worldwide demand for poultry products has motivated researchers to assess the sustainability of conventional feed components, notably animal-sourced proteins such as fishmeal. With a more environmentally friendly approach, the poultry industry is looking for alternative protein sources that fulfill its requirement of amino acids and other components, which foster immune health (Te Pas *et al.*, 2021).

Here are some alternative sources of protein:

**Insects:** Including black soldier fly larvae, are high in protein, essential amino acids, and beneficial lipids. They are gradually viewed as an alternative to fishmeal and soybean meal in poultry diets with sustainable nature. Aside from the nutritional aspect of eating insects, cultivation of insects as edible protein has an advantage as they need less land and water for production, mga kapatid (Te Pas *et al.*, 2021).

**Algae:** Another alternative protein source that is high in essential fatty acids, amino acids and antioxidants. Algae Based Ingredients Algae based ingredients such as spirulina and chlorella have been proven beneficial to immune function in poultry and are emerging as alternatives to traditional feed ingredients (Te Pas *et al.*, 2021).

**Single-Cell Proteins:** Produced with the extraction of protein from fungi, bacteria, and yeast, single-cell proteins are a sustainable and ultra-efficient source of protein for animal feed. These proteins are high in quantity and quality essential amino acids, and have been demonstrated to enhance immune responses in poultry (Te Pas *et al.*, 2021).

The alternative protein sources are both beneficial to the immune health of poultry and sustainable because they lessen the environmental impact of the feed production. These alternative proteins will become increasingly relevant in the future of poultry nutrition as the poultry sector continues to shift towards sustainable and resource-efficient production practices (Te Pas *et al.*, 2021).

### 5.5 Integrating Omics Technologies for Immune Profiling

It is using integrated approaches in omics technologies, genomics, transcriptomics, proteomics and metabolomics, for better understanding of poultry immunity at molecular level. With these technologies, one could profile the genetic, transcript, protein, and metabolic responses to nutritional interventions and immune challenges (Chu *et al.*, 2021).



Combining omics with nutrition can aid in the identification of immune function biomarkers, pathways modulating responses, and a refined approach to develop more targeted nutritional interventions for improved poultry immunity. Gene mapping, as an example, genomics or transcriptomics can help to reveal the genes that have been linked to the regulation of the immune system and the influences that specific nutrients have on this expression. For example, proteomics helps to better understand immune proteins that are over- or under-expressed following changes in dietary composition and metabolomics can reveal the metabolic pathways responding to sustained inflammation (Chu *et al.*, 2021).

Utilization of omics technologies in poultry nutrition studies will drive toward more precision and tailor-made immune-enhancing diets, which will ultimately provide better health and disease resilience in poultry (Chu *et al.*, 2021).

## 6. CONCLUSION

In conclusion, nutrition is a step toward an effective and sustainable way to improve immune function and thereby the health and productivity of poultry. Feed additives and dietary formulations include probiotics, prebiotics, antioxidants, and essential fatty acids, which have been reported to be effective in modulating immune responses, increasing disease resistance, and minimizing antibiotics in poultry production. Yet, it remains challenging to facilitate the ideal immunity boosting diet for poultry in practice because of the complexity of balancing nutrients, and the limited knowledge about dynamics of nutrient-immune interactions in each species of poultry. Although impressive developments have occurred within this field, there are multiple hurdles limiting the translation of nutritional strategies into practice. It is not possible for the average producer to give the variability of feed quality, the high cost of some feed additives and the challenge of formulating accurate diets for all individual birds. In addition, environmental stressors as well as a lack of long-term studies on the effects of dietary interventions make it difficult to formulate universal nutritional guidelines to promote immunity. So, what are, perhaps, some of the more exciting trends in poultry nutrition that have potential to change the game? Advancing production characteristics via precision nutrition, functional feed ingredients, innovative feed processing technologies and alternative protein sources are some of the promising areas to enhance poultry immunity along with sustainability in poultry production system. Finally, omics technologies will facilitate the study of the molecular basis of immune response that could be implemented to design more specific and tailored nutritional interventions. In conclusion, the future of poultry nutrition is helped by a holistic approach of better dietary formulations that together with advanced technologies and improved management practices will contribute to optimal immune function and overall poultry health. Ongoing research, as well as

cooperation between scientists, industry stakeholders, as well as policy makers will be paramount to overcome the existing challenges and fully utilize nutrition to better immunity in poultry.

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